MT-CWJR-091-011

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WORKSHOP REPORT

ADVANCED WELDING SCIENCE FOR DOD APPLICATION

"The Genesis of the Army Welding Microfactory"

March 20-22, 1991
Golden, Colorado 80401

Submitted to:
Army Research Office
Research Triangle Park, NC 27709-2211

Submitted by:
D.L. Olson and G.R. Edwards
Center for Welding and Joining Research
Colorado School of Mines
Golden, Colorado 80401

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prioritization for each area. Specific opportunities were matched to specific needs to suggest project areas where research and development would make contributions providing major technological impact. Various organizational concepts by which welding and joining research, development, and technological transfer could be integrated for maximum impact to achieve the most direct impact were introduced and discussed.

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ABSTRACT

A workshop was held to identify the welding and joining needs of the defense-related industries, and to discuss the opportunities afforded these industries to solve the needs by applying new methodology and knowledge available from the research establishment. These needs and opportunities were given approximate dates of interest which established a crude chronological prioritization for each area. Specific opportunities were matched to specific needs to suggest project areas where research and development would make contributions providing major technological impact. Various organizational concepts by which welding and joining research, development, and technological transfer could be integrated for maximum impact to achieve the most direct impact were introduced and discussed.

1.0 INTRODUCTION

ADVANCED WELDING SCIENCE FOR DOD APPLICATIONS

1.1 Purpose

A three-day workshop was completed to accomplish the following three tasks:

1. To identify, address and assess the welding and joining needs of the manufacturers of technical assemblies and structures for defense.

2. To identify, address and assess the welding and joining opportunities coming from research and development activities.

3. To explore the scope, mission, operation, and managerial structure of a microfactory (including the need for facilities) which: (i) will continually identify the technological needs in the making of technical and structural assemblies. (ii) will continually identify welding and joining research and development concepts and achievements which can be advanced as an opportunity, and (iii) will organize expertise (researchers, developers, welding equipment manufacturers and users) for rapid introduction and utilization of the promising new concepts, materials, processes, and practices to increase defense manufacturers' ability to produce technical and structural assemblies with high integrity, high productivity and high economy.

1.2 Format

The workshop was structured so that the first day addressed the needs and opportunities for weldability and joinability of materials for defense industry technical assemblies and structures. (Weldability and joinability are broadly defined here to mean the response of materials to the welding and joining process). This topical area is important to defense industry manufacturers who are attempting to use new advanced engineered materials to achieve new design requirements. Often material producers have made materials with advantageous properties, but with inadequate levels of fabricability. Careful assessment of present and future materials needs is required to promote timely welding and joining research and development.

The second day of the workshop identified and discussed the welding and joining processing needs and opportunities. Advances in processing can directly relate to increased productivity and savings. Just as critical as the research and development efforts is the clear identifiable path from the laboratory to the production facility.

The major issue of the workshop, a discussion of the concept of a microfactory, was the topic of the last day. The concept was introduced by an invited speaker, who gave a 30-40 minute presentation on the needs for a welding microfactory. Two independent examples of a microfactory were then presented by other invited speakers. These presentations set the stage for a panel discussion.

1.3 Agenda

WORKSHOP

ADVANCED WELDING SCIENCE FOR DOD APPLICATION
"The Genesis of the Army Welding Microfactory"
March 20-22, 1991

Day One - Morning: Weldability and Joinability - Colorado Room

Needs

8:00	Edison Welding Institute Harvey Castner	"Army Welding Survey" (1 hour)
8:45	TACOM Directorate for Design & Manufacturing Technology Jamie M. Florence	"Introduction to Workshop"
9:30	Martin Marietta Astronautics Group Dr. Carl Cross	"Aluminum Welding"
10:30	DTRC Paul Holsberg	"High Strength Structural Steel Welding"
11:00	DTRC Mike Wells	"Titanium Welding"
11:30	Colorado School of Mines Gerald DePoorter	"Ceramic Joining"

Day One - Afternoon: Weldability and Joinability

Opportunities

1:30	Edison Welding Institute Dr. Bob Rivett	"Welding Thermal Plastics"
2:00	Ohio State Univ. Prof. Bud Baeslack	"Advanced Material Joining"
2:30	Univ. of Tenn. Prof. John Landes	"Fitness for Purpose"
3:30	Colorado School of Mines Prof. David Olson	"Predictability-Process and Consumable Selection"
4:00	NIST Dr. Tom Siewert	"Joining of Electronic Materials"

Day One - Evening: Weldability and Joinability

Panel Discussions

Day One Panel Members

Dr. Michael Cieslak (Panel Leader)	Sandia National Laboratories
Dr. Edward Chen	ARO
Prof. Ray Thompson	Univ. of Alabama at Birmingham

Assessment and Prioritization of Needs and Opportunities

Day Two - Morning: Welding and Joining Processes

Needs

8:30	Ingalls Shipbuilding Ovide J. Davis	"Fabrication and Welding of Thin Section"
9:30	NRL Dr. Ed Metzbower	"High Speed Thick Section (Beam) Welding"
10:30	ARO Harry Diamond Labs. Jim Geis	"Joining of Microelectronics"
11:00	IMOG Rocky Flats Plant Dr. Paul Burgardt	"Welding Precision Assemblies"
11:30	MTS Corporation Dr. Dawn White	"In Process Inspection of Welding"

Day Two - Afternoon: Welding and Joining Processes

Opportunities

1:30	INEL Dr. Hershall Smart	"State of Our Physical Understanding of Welding"
2:00	Babcock and Wilcox Martin Kline	"PAWS Program"
2:30	American Welding Institute Dr. Jerry Jones	"Process Control and Neural Control System for Welding"
3:30	NIST Dr. Chris Fortunko	"Advanced NDE for Real Time Process Control"
4:00	EG & G Mound Applied Technologies Eric Johnson	"Statistical Process Control"

Day Two - Evening: Joining Processes

Panel Discussions

Day Two Panel Members

Dr. Jim Key (Panel Leader)	INEL
Don Schwemmer	AMET
Prof. Tom Eager	MIT

Assessment and Prioritization of Needs and Opportunities

Day Three: Genesis of a Microfactory

8:00 Concepts for a Welding Microfactory
Dr. Phil Parrish - BDM

9:00 Example I of Microfactory
Mr. Steve Balint - Army Materiel Command

9:30 Example II of Microfactory
Prof. David Olson

10:30 Panel Discussion for Microfactory

Dr. Andrew Crowson (Panel Leader) (ARO)
Mr. Steve Balint (AMC)
Dr. Jim Kelly (DARPA)
Mr. Donald W. Cargo (TACOM)

2.0 PRIOR ASSESSMENTS OF WELDING RESEARCH AND DEVELOPMENT

The following summations and recommendations were taken from prior reviews in the 1980's. These reports are valuable and should be referenced in perspective to effectively use the information and recommendations of this report.

2.1 1982 NMAB REPORT "ADVANCED JOINING TECHNOLOGY" (1)

Maximum use should be made of existing knowledge in joining technology. A large body of scientific information, technical data and applied scientific and engineering knowledge pertinent to joining technology exists. Joining methods, procedures, and materials therefore do not generally need to be selected empirically. Basic information, concerning many welding processes, particularly advanced techniques, is limited, and the physical property data available for some engineering alloys are not sufficient to permit accurate heat-flow calculations. Weldment properties cannot be predicted in most cases from process, filler-metal and parent-metal data.

The following basic welding research needs apply to all the materials covered by this report unless otherwise stated.

Research should be continued to provide improved understanding of the various aspects of the joining processes with particular emphasis on topics such as: metallurgical interactions, phase transformations, high temperature diffusion, galvanic corrosion effects, mismatch of physical and mechanical properties of filler and base metals, cleaning and joint preparation, diffusion and phase transformations, weld pool chemical reactions, heat generation and transport, stress analysis, defects, and fracture mechanics, fluxes and health hazards.

Increased emphasis in welding research should be placed on the first step of the scientific method (i.e., making extensive observations of the entire process) rather than only focusing on a specific limiting behavior. Programs should be developed to transfer the results of these scientific studies to the welding engineering and design community. This is of basic importance because weld properties are related to composition and prior history that include material response to the thermal activity associated with welding. A fundamental understanding of the influence of the welding process on weld integrity requires complete description of the thermal conditions.

2.2 1983 THE STATUS OF WELDING TECHNOLOGY IN THE UNITED STATES (2)

An analysis of the foregoing information suggests the following conclusions with respect to the status of welding technology in the U.S.:

1. The quality of the U.S. technological effort in welding, including institute and industrial research, is about on a par with that of any country in the free world.

2. On a gross domestic product basis, expenditures on research are competitive with other industrialized nations; but on a manpower effort and research results basis, the U.S. research effort is clearly behind that of Japan, Germany, and the U.K.

3. The implementation of research results or reduction to practice has been falling increasingly behind that of other industrialized nations because of economic deterrents.

4. Welding research and technology in the U.S. are relatively uncoordinated, resulting in undesirable duplication and a reduced return on research investment.

The problem of lagging welding technology in the U.S. has been recognized for a number of years and was the subject of Henniker conferences in 1976 and again in 1978.

The standard of living in industrialized countries is strongly influenced by each country's technology base through its effect on productivity and the manufacturing segment of the gross domestic product. Consequently, if the United States is to retain its standard of living and remain internationally competitive industrially, it must support the research that maintains its technology base. As a generic technology that broadly influences productivity in many industries, welding and joining deserve special attention in this regard.

An analysis of available information suggests that significant sums are being invested in welding research in the United States. This applies to university research, industrial research and government research. In terms of money invested in welding research, the United States appears to be competitive with other countries. This is also true with respect to the scope of research being undertaken and the caliber of personnel involved in welding research. However, the technology base in welding is believed to be eroding compared with other countries because compensation disparities reduce the return of research results for a comparable investment. In addition, and probably most important, there is little coordination of the welding research effort in the United States, which again significantly reduces the return of investment. Countries with a large, centralized welding research facility or other effective means of coordinating research have a significant advantage in this respect.

Coordination of the U.S. welding research effort is imperative if this country is to remain competitive with other industrial nations.

2.3 1984 WELDING RESEARCH COUNCIL BULLETIN "CURRENT WELDING RESEARCH PROBLEMS" (3)

It has recently been determined that over half of the Gross National Product is associated in one way or another with welding and joining processes. Also, the White House Office of Science and Technology has designated welding as one of the three national needs. Thus, there has been considerable effort in the United States to increase the country's ability to expand welding technology. A result of this effort is the recent establishment of the American Welding Technology Application Center (AWTAC) now AWI. One of the purposes of AWTAC is to encourage, stimulate, and guide the research, development, and improvement of needed welding technology by other organizations such as private companies and not-for-profit research groups, including universities.

The Welding Research Council periodically conducts surveys to assist in determining research needs. This Bulletin summarizes the results of the current WRC survey. The survey was conducted through the various WRC Project

Committees, and includes suggestions from industry, government agencies, and universities.

The national concern regarding the future of welding research has recently resulted in two additional surveys to identify current welding problems. One of these was co-sponsored by the Welding Task Group of the Committee on Materials (COMAT), the Welding Research Council, the American Welding Society, and the American Society for Metals. The other recent survey was initiated by the Office of Naval Research (ONR) to identify needs for fundamental welding research. The results of these two surveys are also included in this bulletin.

The surveys by WRC, COMAT, and ONR resulted in over 200 suggestions. The suggested problems range across the entire spectrum of welding technology, from practical application-oriented problems to those requiring research for basic understanding. Some of the problems are so broad and complex that their solution requires the coordinated effort and knowledge of experts in many branches of engineering and science, with input from the entire welding community. The problems, and their solution, should be of interest to welding engineers, materials scientists, designers, fabricators and users, as well as to those engaged in industrial and university research.

This list is published to assist universities, industrial and research organizations, and government agencies by pointing out to them the welding problems/needs requiring solution or additional study. These submittals have been provided to the University Research Committee by members of the WRC Project Committees, the attendees at the Conference on the National Needs in Welding Technology on April 28, 1983, and the participants at the ONR Welding Science Workshop on March 24-25, 1983.

2.4 1985 UNITED STATES ARMY WELDING RESEARCH AND DEVELOPMENT TOPICAL AND COORDINATION MEETING (4)

The United States Army Welding Research and Development Topical and Coordination Meeting, February 5-8, 1985 was held at the Colorado School of Mines to identify specific concerns and technical research and development needs.

<u>Non-Technical Concerns</u>

1. An interagency code committee needs to be established to develop standard codes and to simplify codes. This committee needs to achieve a methodology to better work with the small business shops.

2. There is an unacceptable welding engineering manpower shortage in all of the Army facilities. This manpower shortage affects cost effectiveness, productivity and ability to translate technical improvements into the manufacturing of assemblies.

3. Design engineers need to be more aware of joining concerns.

4. There is a need for a forum for interagency communications as to welding and joining concerns.

5. Review of the certification and training practice being used by the U.S. Army in both production and field welding is needed.

6. Welding and joining information transfer with National Laboratories (i.e. Los Alamos National Laboratories) and with welding institutes like the American Welding Institute and/or the Edison Welding Institute needs to be established.

Technical Research and Development Needs

The panel of reviewers identified the following joining research needs and have listed them in their priority of need.

1. Adaptive process control (sensor development and applications).

2. Real time non-destructive evaluation (sensor development and applications).

3. Consumables.

    a. Multiple purpose filler metal for repair.
    b. Advanced consumables.
    c. Refining of existing consumables.
    d. Flux cored wire development.
    e. New aluminum consumables based on new compositional concepts.
    f. Cold wire feed materials for electron beam welding.

4. Repair technology - including use of robots to reduce need for repair.

5. Weldability and process development for welding metal matrix composites and ceramics.

    a. There is a need to evaluate joining concepts early in the development and selection of new advanced materials.

6. Welding of recycled alloys.

    The concern is in many alloy systems and not just in super alloys. Mini steel mill concepts and the recycling industry are introducing residual contaminants into defense related materials. Research is needed to understand the role of the various microalloy additions (contaminants) on the weldability and mechanical integrity of structural material which are associated with these recycling streams.

7. "Fitness for Purpose" research.

    The efforts of the last ten years need to be continued in order to use our mechanical analytical ability to allow better selection and use of materials which are to be welded. This "fitness for purpose" research should center around weldment materials (fusion and heat affected zones) since they are the least understood due to the heterogeneous nature of their microstructure.

8. High productivity welding of complex joints.

   Methods to automate welding of complex joints need to be addressed. Adoptive feedback control systems using robotic welding systems is a key issue.

9. Solid state bonding.

   The research need is seen for both low temperature and high temperature bonding processes. Included in this solid state bonding research initiative is explosive bonding, flash, friction and inertial welding processes. Advancements in the utilization of dissimilar metal joined assemblies will result from this solid state bonding research.

10. Quantitative prediction of distortion.

    The lack of data necessary to effectively use the computer analytical techniques that have been generated over the last decade was recognized. It is essential that physical properties for engineering materials, including weld metal, be determined as a function of temperature. Analytical techniques to calculate distortion and shrinkage during multiple pass welding are needed since most structural assemblies of interest are of thickness requiring multiple weld deposits.

11. Ion implantation.

    Ion implantation needs to be used more effectively to produce surface modification for wear and corrosion resistance. Ion implantation coupled with surface modification by laser, EB, and GTA surface heating can improve surface properties.

12. Environmental issues.

    Personnel are closely associated in these joining processes which can generate hazardous radiation and fumes depending on the welding process. Research projects should be initiated to alleviate or reduce the health and safety hazards. This concern could be addressed either directly or indirectly by promoting the national health and safety funding agencies to address the standards and concerns of the welding workplace.

2.5 1987 NMAB REPORT "CONTROL OF WELDING PROCESS" (5)

Recommendations

1. Research in welding should not be limited to the traditional metallurgical and mechanical properties of weldments, as has often been the case in the past. Welding controls should be considered a research topic, and output should focus on the results of interdisciplinary team efforts.

2. Generic research should be supported on the principles and procedures for implementing flexible welding work cells. The generic intelligent fixture is a goal of many disciplines in advanced manufacturing systems, and the welding industry is no exception. It may be possible to find new relationships between transduced signals in the fixturing and residual stress and distortion. This area of investigation should include computer-aided tooling design and manufacture.

3. Research should be conducted on interpreting the output of readily available sensors in terms of welding process variables and in terms of the ultimate weld quality and fitness of purpose.

4. New ideas for real-time sensing of weld process variables should be pursued. For example, there is a need for voltage-drop measurements that are independent of contact tube design, for temperature measurements near the weld pool surface, and for reliable information on pool solidification.

5. Sensing and model research should not be pursued in isolation. They must be integrated to achieve desired results in the production system.

6. Welding process control research work is appropriate for funding by both mission-oriented and basic research governmental institutions. Because of the systems nature of welding processes and controls, it is important that there be some national coordination directed toward relating the different research activities in agencies, universities, and centers. Effort should not be channeled to any one group, but rather innovation and creativity in the application of the welding sciences should be encouraged across a broad front, including NSF and other government agencies. A closer tie between the welding research community and academia is needed so that the educational role of welding research application and process technology is transmitted to engineering education.

3.0 EWI ASSESSMENT OF ARMY WELDING DEVELOPMENT NEEDS (6) - Summary of EWI Report by Harvey Castner

This presentation describes an initial assessment of the current state of welding practice and opportunities for improvement of welding practice in the Army Materiels Command (AMC). This assessment covers AMC commodity commands, laboratories, arsenals and maintenance depots. Deficiencies in welding technology and opportunities to develop and apply new welding technology to support present and future Army weapons systems include:

- Design and Fitness-For-Service
- Material Properties and Performance
- Emerging and Advanced Processes
- Automation and Process Control
- Quality and NDE
- Repair and Maintainability

DESIGN NEEDS

- Reduced Weight and Improved Performance
- Fitness-For-Service Design
- Automation of Engineering Functions
- Expert Design Aids
- Discontinuity Acceptance Guidelines
- Revised Standards and Specifications

MATERIALS NEEDS

- Procedures for New Materials
- Joining of Advanced Materials
- Joining of Composites
- Improved Weld Properties
- Weldability and Consumables Data Base

EMERGING AND ADVANCED PROCESSES

- Basic Process Science and Modeling
- Laser Welding and Cutting
- Solid State Processes
- Joining of Electronic Composites
- Thermal Coating
- Advanced Arc Processes

AUTOMATION

- Design for Automation
- Robotic Welding
- Flexible Automation

PROCESS CONTROL

- o Real-Time Process Control
- o Advanced Sensors
- o Process Modeling
- o Intelligent Control Systems

QUALITY AND NDE

- o Process Parameter/Weld Quality Research
- o Real-Time Quality Monitors
- o Statistical Process Control
- o Advanced Quality Monitors

REPAIR AND MAINTAINABILITY

- o Advanced Materials and Composites
- o Expanded Repair Capabilities
- o Field Repair

4.0 PRESENT STATE OF OUR PHYSICAL UNDERSTANDING OF WELDING SCIENCE (7)

Dr. Hershal Smartt, Idaho National Engineering Laboratory

Welding is interdisciplinary science and engineering involving expertise in fundamentals of processes (energy, mass, force), and materials. It requires understanding of folklore, experimental observations and theoretical results. Efforts are leading to predictive models. Physical understanding is needed to obtain weld/weldment performance/reliability, fitness for service, and economy.

Predictive models are needed to provide the welding engineer with tools to support procedure development, weldment design, process development, and materials development and automation/process control.

Understanding of underlying science is reasonably mature which includes heat transfer, mass transfer, fluid dynamics, thermodynamics, physical chemistry, thermodynamics, phase transformation, etc. Application of this science to welding is essentially static and uncoupled. Experimental measurement of the dynamic state of welding is significantly limited by lack of appropriate sensors.

Welding science has evolved to the point where many, if not most, of the important unsolved problems are multidisciplinary. This results mainly from the coupling of process, materials, and weldment physics.

5.0 THE WORKSHOP - FIRST DAY: WELDABILITY AND JOINABILITY

In the first morning session invited speakers addressed the weldability and joinability concerns for specific defense materials or product areas. The invited speaker came with handouts which recorded clear, concise statements of five or six needs.

Day One - Morning: Weldability and Joinability Needs

Martin Marietta (Denver) Dr. Carl Cross	"Aluminum Welding"
DTRC Paul Holsberg	"High Strength Structural Steel Welding"
DTRC Michael Wells	"Titanium Welding"
CSM Dr. Gerald DePoorter	"Ceramic Joining"

After each presentation, the speakers led a discussion involving all participants. Other needs were suggested and included for the panel discussion which was held that evening. This approach provided at least five identifiable needs for each area, and also provided a method to prevent important omissions. All of these needs are described in this workshop report.

In the afternoon of the first day of the workshop, invited speakers introduced three to five specific opportunities in their specified discipline area which would make meaningful contributions to the manufacturing of defense products. The afternoon speakers used the same format as the morning speakers and came to the workshop with handouts that were distributed to all of the participants at the workshop. (These documents are included in this workshop report.) The invited speakers representing the specified research areas are given below:

Day One - Afternoon: Weldability and Joinability Opportunities

EWI Bob Rivett	"Welding Thermal Plastics"
Ohio State Univ. Prof. Bud Baeslak	"Advanced Materials Joining"
Univ. of Tenn. Prof. John Landes	"Fitness for Purpose"
Colorado School of Mines Prof. David Olson	"Predictability-Equal Property Diagrams"
NIST Dr. Tom Siewert	"Joining of Electronic Materials"

After a full day of introducing needs and opportunities in the area of weldability and joinability, a panel was convened during the evening of the first day. The panel assessed, prioritized and discussed these specific weldability and joinability needs and opportunities.

5.1 Weldability Panel Report

SUBJECT: Weldability and Joinability

PANEL MEMBERS: Dr. Michael J. Cieslak - Sandia Nat. Laboratories (Leader)
Dr. Edward Chen - Army Research Office
Dr. Andrew Crowson - Army Research Office
Prof. Raymond Thompson - Univ. of Alabama-Birmingham

Reports were presented by several eminent individuals in the area of materials weldability and joinability (see attached list). The purpose of these presentations was to: (1) inform ARO of the present status of technology in the various topical areas, (2) identify needs in these areas, and (3) illuminate potential opportunities that exist either as established technologies or near-term capabilities which could be used to advance ARO's technology and manufacturing base.

Although an extremely wide range of materials was discussed, several topics continued to appear as needs, independent of material. It was clear that although metallurgical joining science had progressed rapidly over the past 20 years, fundamental data, or rather the lack thereof, severely limits our ability to quantitatively predict weld metal geometry and properties. The determination of critical materials properties, both kinetic and thermodynamic, and those necessary to develop constitutive relationships, was the primary need identified by the speakers and the participants.

Second among the needs in terms of responses from the participants was the need for standardization of weldability tests, both those involving solidification and liquation cracking, and those involving hydrogen embrittlement and solid state failure.

Analytical modeling was identified as a need but the consensus among the participants was that this topic and the related topics of sensors, equipment, and process development would be addressed by the second day panel on processing.

Next was the subject of fitness for service based upon a fracture mechanics perspective. It was noted among the participants that although a vast amount of information is already available, there is a general problem of having no "championing" organization willing to step forward to be the first to accept the concept of fracture mechanics design and acceptance of hardware and structure. Instead, the costly approach of "workmanship"-based product acceptance (i.e. no flaws allowed) permeates the manufacturing base. Aside from being a costly economic concern, this approach is fundamentally at odds with both intelligent design and a quality-based production ethic. Furthermore, a continuation of this criteria leads to an understanding of the net result of improved NDE techniques. That is, as subtler defects are

identified, more product will be rejected or reworked, leading to a decrease in manufacturing productivity.

Among opportunities listed, the most consistently mentioned involved the present-day ability to perform very sophisticated metallurgical analysis. Advanced materials, in addition to many present-day materials, cannot be fully understood or applied with confidence to engineering designs until their properties subsequent to (and even during) the joining are established.

This ability to develop materials science based understanding of joined materials directly influences our ability to develop appropriate consumables for emerging or advanced materials. The time frame for alloy consumable development must necessarily track the time frame for the base material as the structure/property data base required for the two is essentially identical.

The state of the science in fitness for purpose (or fracture-mechanics based design) design and product acceptance is ready (in fact has been ready) to be applied to a wide variety of materials and applications. With the completion of standards documents, it should be possible to incorporate this design philosophy into product definition, at least for hardware and structures constructed from simple alloys, beginning with three years. The exception to this lies in the area of ballistic (i.e. high $\dot{\epsilon}$) designs. Yet even in this area, there are opportunities as many organizations, especially those within the DOE nuclear weapons complex, are developing data, test techniques, and predictive capabilities for understanding material response to hypersonic impact.

The area of electronic materials and processing, especially solder processing, is an area holding great opportunity. Some indication of this is realized by the broad response of individuals in identifying this topic even though very few centers for joining have programs in this area. Better understanding of solder metallurgy and processing is the key to improved microelectronics processing. It was stated that solder metallurgy/processing today is at the same state in its development as welding metallurgy was four decades ago. Within 3-5 years an understanding and the implication of solder wettability will be established, having enormous impact in microelectronics fabrication. In the same time frame, great improvements in metallization will be identified and implemented. The effect and influence of intermetallics will be quantified in 5-10 years, and lifetime prediction techniques will exist for solder joints. Improved solder alloys will be developed, including "structural" solders, as will lead-free solders. Improved soldering techniques involving lasers, ultrasonics, plasmas and other energy sources will come on the market. Because the state of the technology is so immature, ARO can have a substantial impact in providing direction and focus by interactions with the leading research sites in this area.

Other areas involving process resiliency, NDE/inspection, environmental issues, analytical modeling/sensors, thermoplastics and equipment were identified, but each to a lesser extent than those listed above.

It is clear from the presentations and discussion and from the responses of participants that the joining community is in a position now and in the near future to provide the materials information, both chemical (kinetic and thermodynamic) and mechanical (constitutive equations, i.e. $\sigma = f(\epsilon^n, \dot{\epsilon}^m, T,$

t...) on the materials required for ARO applications in a 5-10 year horizon frame. For advanced materials, some techniques need to be refined, modified, or developed. But the present day intellectual property within this community provides the necessary basis for correct development of required techniques. It is interesting to note that there was a broad consensus among all present that for analytical modeling efforts to be successful and pertinent as engineering tools, we must have the appropriate materials data bases input information.

The remainder of this report consists of three tables. Table I is a roadmap describing how to get to the holy grail, "Intelligent product acceptance". Section 5.2 lists recommended material property and behavior needs on a projected time scale. Section 5.3 lists the needs by schedule of time of need. Section 5.3 also gives the scopes of these needed projects suggested by the participants and panel members. Section 5.4 is a similar table of opportunities. Section 5.5 describes the specific opportunities to enhance our ability to weld and join materials and indicates a suggested time when each opportunity will become available. For the purpose of this report, a need is defined as a technological problem requiring a solution (it may be quite fundamental with broad impact or very specific) and an opportunity is defined as a capability which can be applied to a need.

Table I PROCESSING, MICROSTRUCTURE AND PROPERTIES

FUNDAMENTAL MATERIALS UNDERSTANDING

- CONSTITUTIVE RELATIONS
- KINETIC/THERMODYNAMICS UNDERSTANDING

FUNDAMENTAL PHYSICAL(PROCESS) UNDERSTANDING

- ENERGY SOURCE - MATERIAL INTERACTION
- SUBSURFACE PHYSICAL BEHAVIOR (WHAT HAPPENS BELOW THE SURFACE)

APPROPRIATE WELDABILITY TESTS

CORRECT PROCESSING PARAMETERS

APPROPRIATE AND ACCURATE MATHEMATICAL MODELS

↓

INTELLIGENT DESIGN GUIDANCE

↓

INTELLIGENT WELD PROCESSING

↓

INTELLIGENT PRODUCT ACCEPTANCE

5.2 Materials Property Data and Behavior Needs

5.2.1 Kinetic/Thermodynamic Data

1-5 Years

Transition Strengthening Steels ($\leq$130 KSI YS)

High Strength Aluminum

High Grade Titanium

5-10 Years

$\geq$150 KSI YS, Steel

Aluminum-Lithium Alloys

Low Grade Titanium

Advanced Polymers/Ceramics

>10 Years

> 150 KSI, High K_{IC} Steel

Aluminum Particulate Alloys

Titanium Intermetallics

Ceramic Matrix Composites

>12 Years

Intermetallic Matrix Composites

5.2.2 NDE Inspection

3-5 Years	Small Defects Identifiable
5-10 Years	Real Time Non Destructive Evaluation
>10 Years	Non Destructive Evaluation of Composite Materials

5.2.3 Process Control

Now	Heuristic Based Control
1-5 Years	Single Variable/Input Control
5-10 Years	Multivariate Control
>20 Years	Neural Network Systems

5.2.4 Constitutive (Mechanical) Data

0-5 Years	Simple Wrought Alloys
5-10 Years	Simple Particulate Loaded and Heterogeneous Materials
>10 Years	Composite Materials
1-5 Years	Room Temperature Properties
5-10 Years	Near Solidus Properties
5-10 Years	Mushy Zone Properties for Simple Model Systems
>10 Years	Mushy Zone Properties for Complex Alloys

5.2.5 Materials Data

1-5 Years	Simple Wrought Products
5-10 Years	Heterogeneous Metallic Alloys
>15 Years	Non-Metallic Composites

5.2.6 Weldability Tests

5-10 Years	Standardize Hot Cracking Tests
5-10 Years	Standardize Cold Cracking Tests

5.2.7 Analytical Modeling

Now	Heuristic Based Prediction
1-5 Years	Partial Predictive Capabilities
>10 Years	Complete Geometry and Properties (Residual Stress, Defects, Microstructure) Prediction

5.2.8 Fracture Mechanics Based Design

3-5 Years	Simple Materials
5-10 Years	Heterogeneous Metallic Alloys
>15 Years	Composites

5.3 SCOPES FOR SPECIFIC WELDABILITY AND JOINABILITY NEEDS

5.3.1 High Strength/Weight Alloy Weldability Needs

Present	1995	2000	2005
(a) Joining of Aluminum-Lithium Alloys			
	(b) Aluminum Weld Metal Grain Refinement		
		(c) Fundamental Understanding of Aluminum Weld Defects	
(d) Characteristics of Titanium Welding that Impact Cost			
(e) Design for Titanium Fabrication			
	(f) Reduced Contamination Potential of Titanium Welds		
	(g) Alternative Weld Preparation for Titanium Welds		
	(h) Titanium Welding Process Development		
	(i) Backing Materials for Full Protection of Titanium Weld		
		(j) Acceptance Criteria for Interstitial Contamination of Titanium Welds	
		(k) Control of Weld Residual Stress in Titanium Welds	

JOINING OF ALUMINUM-LITHIUM ALLOYS (8)

Use of new high strength Al-Cu-Li alloys (e.g.: Alloys 8090, 2090, and Weldalite™ 049) in welded structures (e.g.: bridge supports, armor plate and cryogenic tanks) has great potential for improved performance over existing materials. Weld development and characterization is in its infancy with more work needed (including studies of microstructure, corrosion behavior, strength and heat treatment, and ballistic properties). Welding problems inherent to lithium containing alloys include susceptibility to porosity and poor fluidity (1991).

ALUMINUM WELD METAL GRAIN REFINEMENT (8)

Titanium or zirconium additions are commonly made to filler alloys for purposes of grain refinement. Grain refinement results in multiple benefits including improved strength and toughness and resistance to hot tearing. However, recent studies have shown that it is not sufficient just to have these elements present; they must be present in the weld pool, apriori, in compound form ($TiAl_3$ or $ZrAl_3$) capable of serving as nucleants when attached to the solidification front. For optimum refinement, these compounds should be present in the filler metal with a given size distribution, controlled through thermal-mechanical processing, such that for a given weld pool residence time, dissolution will yield a modified (smaller) size distribution resulting in many nucleation events. Production of such a filler wire needs to be investigated and compared with conventionally processed filler wire (1995).

FUNDAMENTAL UNDERSTANDING OF THE FORMATION OF ALUMINUM WELD DEFECTS (8)

The basic defects which continue to guile and hamper weld development of aluminum alloys are porosity, hot tearing and liquation. Although much has been done to understand and model these defects, continued work is needed to fully explain observed behavior. For example, new high resolution insitu radiographic techniques should be used to observe defect formation. A unidirectional solidification apparatus could be devised to simulate and study weld solidification. The connection between microporosity and hot tear nucleation needs to be investigated (2000).

CHARACTERISTICS OF TITANIUM THAT NEGATIVELY IMPACT FABRICATION COSTS (9)

Titanium alloys are highly reactive with atmospheric elements at elevated temperatures. Titanium alloys are susceptible to stress corrosion by chlorides from grease and oil. Titanium is more difficult to machine and grind than most construction materials. Titanium is nonmagnetic. Research to design processes to alleviate these hinderances needs to be developed and performed (1991).

DESIGN FOR TITANIUM FABRICATION (9)

Structures are not generally designed to optimize the welding of titanium. A potential improvement would result if titanium welding engineers would work with structural designers to identify acceptable welding process/position/joint design combinations. It is also possible to exploit new manufacturing processes, such as corrugated core and superplastic forming/diffusion bonding (1992).

REDUCED CONTAMINATION POTENTIAL OF TITANIUM WELDMENTS (9)

Titanium alloys are susceptible to weld contamination from dissolved oxygen and nitrogen, porosity from air aspiration and restraint cracking in contaminated thick section weldments. The result is defect removal and repair costs for titanium exceeding those for high strength steel. In-process sensors to monitor interstitial content and novel post-weld inspection techniques need to be developed (1995).

ALTERNATIVE JOINT/WELD PREPARATION PROCEDURES FOR TITANIUM WELDING (9)

Preparing the joint bevel is labor intensive. Special handling and environmental precautions are required prior to welding. Novel cutting methods and alternative solutions need to be developed (1995).

TITANIUM WELDING PROCESS DEVELOPMENT (9)

Low productivity with conventional titanium welding processes is a problem. GTAW process is limited to the flat position. All position GMAW requires high skill level to minimize porosity and spatter. Synergic pulsed GMAW and burried-arc GTAW need to be evaluated (1992). Advanced processes such as ESW, EBW and laser welding need to be exploited. Flux core technology needs to be developed (1995).

BACKING MATERIALS FOR FULL PENETRATION SINGLE-SIDED WELDING OF TITANIUM (9)

Limited methods exist to protect the backside of titanium weldments from atmospheric contamination. Modified joint designs and non-hygroscopic backing tapes need to be developed (1995).

ACCEPTANCE CRITERIA FOR INTERSTITIAL CONTAMINATION OF TITANIUM WELDMENTS (9)

Weld contamination can reduce the ductility and toughness of titanium weldments. The maximum acceptable level of interstitial contaminants in titanium weld metal that will not degrade mechanical properties must be defined. Also sensitivity analyses to identify repair/rework procedures need to be performed (2000).

CONTROL OF WELD DISTORTION/RESIDUAL STRESSES IN TITANIUM WELDMENTS (9)

Titanium has a lower modulus of elasticity than steel. In thicker sections, locked-in strains will be higher in titanium than in steel. Novel holddown tooling/joint designs and analytical methods need to be developed (2000).

5.3.2 Ceramic and Composite Joinability Needs

Present	1995	2000	2005
(a) Toughening of Ceramic Joints			
	(b) Recognize the Full Cost of Developing New Materials		
	(c) NDE of Advanced Material Joints		
	(d) Analytical Modeling of Ceramic Joining		
	(e) Develop Science and Technology of Joining Dissimilar Materials		
	(f) Repair Technology for Joining Dissimilar Materials		
	(g) Primary Fabrication of Thermoplastic Composites		
	(h) Joining Techniques for Ceramic Composites		
	(i) Joining of Aluminum Matrix Composites		
		(j) Corrosion Protection with Thermoplastics	
		(k) Design Joinability into Advanced Materials	
		(l) Ceramic Joining Code Catalog	

TOUGHENING OF CERAMIC TO CERAMIC JOINTS USING VITREOUS FILLER MATERIALS (10)

Joints between ceramic components can be made using vitreous or glassy filler materials. The microstructure of the joint area will be vitreous compared to the crystalline microstructure of the ceramic materials being joined. This will result in different high temperature mechanical properties in the joint compared to the bulk of the ceramic. Enhanced crystallization of intergranular vitreous phases in ceramics has been shown to toughen alumina ceramics. The effects of crystallization or devitrification of vitreous filler materials in ceramic to ceramic joints on both room temperature and high temperature mechanical properties of the joints need to be evaluated (1991).

RECOGNIZE THE FULL COST OF DEVELOPING NEW STRUCTURAL MATERIALS (11)

Although a new material can be demonstrated in the laboratory for $1-2M, the development and qualification of fabrication methods and performance tests costs ten to twenty times as much. If we want to use advanced materials, we must focus our resources on a few materials and applications (1992).

NONDESTRUCTIVE EVALUATION OF ADVANCED MATERIAL JOINTS (12)

New, more sophisticated NDE methods are being developed for both the evaluation of joint integrity and characterization of the joint structure (e.g. nature of interface in solid-state joints).

Use of higher strength/modulus, limited toughness advanced materials (e.g. aluminides, composites, high-strength aluminum alloys and steels) in fracture critical applications will require greater resolution/sensitivity in NDE systems from both initial fabrication and life cycle aspects.

Joint types and materials will make effective NDE increasingly difficult.

- dissimilar material joints create problems due to differences in acoustic characteristics, density, etc.
- composite materials are strongly influenced by interfacial properties.
- solid-state joints are difficult to characterize (1992)

ANALYTICAL MODELING OF CERAMIC JOINING PROCESSES (10)

Differential thermal expansion of the material being joined and the filler material will generate thermal stresses during the joining process. A quantitative stress-strain-temperature history of the joining process will allow joining process simulations to be done. These process simulations can be used to improve mechanical strength of the joint through processing cycle control of residual stress and strains. Constitutive properties for the materials used and computational procedures need to be developed. Both thermal and mechanical analyses must be included (1994).

DEVELOP SCIENCE AND TECHNOLOGY OF JOINING DISSIMILAR MATERIALS (12)

Realization of complex structures utilizing advanced and conventional materials will require their effective dissimilar joining.

The cost-effective use of advanced materials will mandate a greater number of dissimilar material joints per assembly/structure.

Many new materials will never be used unless they can be joined to themselves and to dissimilar materials. A "graveyard" of former "advanced materials" has already been put to rest for this reason.

Increased requirements for development of non-fusion joining processes.
- diffusion bonding, diffusion brazing (TLP)
- conventional brazing and soldering
- adhesive bonding
- hybrid joining processes

Need for enhanced postweld processing.
- post weld heat treatment for stress relief, microstructure stabilization, microstructure modification
- hot-isostatic pressing to repair weld defects (1994)

REPAIR TECHNOLOGY FOR THERMOPLASTIC COMPOSITES (13)

Repair of composite structures can be fast. Readily available welding power sources are useful. Processing is easily understood, intuitive. Repairs can be reliable. Repair technologies for both thermosets and thermoplastics are still being developed. Adhesive technology is slow but relatively more developed than welding. Process technology has been demonstrated but it needs to be simplified (1994).

PRIMARY FABRICATION OF THERMOPLASTIC COMPOSITES (13)

Structures of any size can be joined with high manufacturing productivity and reliability. Joints can have complex shape.

Thermoplastic joining processes have been identified and demonstrated. Status is that of metal welding approximately 70 years ago. Some understanding of polymer structures exists but it must be developed, much as the field of metallurgy for metals.

Long term performance of joints should be similar to that of the parent composite but this has not been proved. Joint design data needs to be developed, design allowables determined.

Control technologies are at an early stage. Additional technologies need to be evaluated, demonstrated, and developed (1995).

JOINING TECHNIQUES FOR CERAMIC COMPOSITES (10)

Ceramic matrix composites will be utilized more in the future as their development matures. Ceramic matrix composites can be used in assemblies where they may be joined to metals, non-composite ceramics, metal-matrix composites, and ceramic composites. The similarities and differences in joining techniques for composites and non-composite materials need to be determined. A compilation of joining techniques needs to be collected and distributed to potential users. This approach will provide a starting place and may reduce duplication of efforts (1996).

JOINING OF ALUMINUM MATRIX COMPOSITES (8)

The arc welding of Al-SiC and Al-Al_2O_3 metal matrix composites has been accomplished, but not without difficulty and limited efficiency. Problems with poor heat conduction and poor fluidity, as well as particle damage and porosity generation, limits the effectiveness of arc welding methods. The superposition of high frequency current pulsation to generate streaming (stirring) effects needs investigation. Another promising method for joining composites is transient-liquid-phase (TLP) bonding, where an interface layer of a eutectic forming element melts upon diffusion into the substrate at elevated temperature. If the eutectic temperature is sufficiently low (e.g.: gallium), the processing will not damage the composite temper resulting in nearly 100 pct. joint efficiency. High frequency (HF) welding is yet another potentially viable means to join composites where high frequency current results in superficial melting of flaying surfaces, minimizing damage to the substrate. Both TLP and HF joining methods warrant further development (1995).

CORROSION PROTECTION WITH THERMOPLASTICS (13)

Coating with thermoplastics could provide thick, void free barriers. Thick coatings can also dampen sound. Alternatively, thick coatings properly formulated, might reduce radar signatures.

Flame spraying technology for thermoplastics exists and coatings have been made that are void free. The number of thermoplastic systems examined has been very limited. Effects of coating formulation have not been examined (2000).

DESIGN "JOINABILITY" INTO ADVANCED MATERIALS (12)

Many advanced materials will not be utilized due to their inability to be effectively joined. Capabilities to produce both a high integrity, high efficiency joints, and methodologies to join materials need to be considered for less demanding applications (2000)

CERAMIC JOINING CODE CATALOG (14)

Relevant codes for ceramic joining from all sources need to be cataloged. This work should acquire codes and assess capabilities. Codes need to be evaluated and modified for unique applications (2000).

5.3.3 <u>High Strength Steel Weldability Needs</u>

Present	1995	2000	2005

(a) Better Characterization of HAZ

(b) High Energy Welding of High Strength Steel

(c) Ultrahigh Strength Steel

BETTER CHARACTERIZATION OF HAZ ZONES (15)

The fracture toughness characterization of a weldment varies with the particular zone being characterized. Very often the heat affected zone, HAZ, exhibits the worst toughness but even the HAZ represents several zones with varieties of toughness. With a standard method for defining these areas within the HAZ and a standard test method for the placement of the defect, the fracture characterization of the HAZ can be better defined. With better defined toughness, statistical models can be used to better characterize probability of fracture in a welded structure (1993).

HIGH ENERGY WELDING OF HIGH STRENGTH STEEL (16)

High energy welding refers to processes such as plasma (PAW), buried gas tungsten arc (BGTAW), electroslag (ESW), electron beam (EBW) and laser (EBW) welding. These processes tend to produce single pass autogeneous welds. They therefore should be considered for the more modern steels such as HSLA or AC/DQ types. Applicability to field welding and thickness range limitations need to be determined. Automation requirements must also be determined (1995).

ULTRA HIGH STRENGTH STEELS (16)

It seems there is always an application for another tough steel with yield strength in excess of 150,000 psi. The plate makers are gaining experience and are designing steels which have good properties and cracking resistance in the HAZ. Consumable development at these strength levels needs to be undertaken now so that these steels can be efficiently utilized. The concept of using lower strength weld metals should also be investigated (2005).

5.3.4 Weldability Tests and Analytical Needs

Present	1995	2000	2005

(a) Weldability Testing
(b) High Strength Steel Weldability Tests for Cold Cracking

(c) Method to Access Susceptibility for Hydrogen and Stress Corrosion Cracking
(d) Standardization of Test Data
(e) Development of Weldability Tests
(f) Performance vs Quality of Solid State Joints

WELDABILITY TESTING (17)

Selection of appropriate weldability tests needs to be understood. Understanding fundamentals associated with specific weldability tests is important in establishing selection rules. Standardization of equipment and test techniques needs to be accomplished. Interlaboratory testing needs to be performed to increase confidence in weldability tests (1991).

HIGH STRENGTH STRUCTURAL STEELS IN QUANTIFIABLE WELDABILITY TESTS FOR COLD CRACKING (16)

Develop weldability test methods applicable to both weld deposits and parent metal to quantify cold (delayed, hydrogen assisted) cracking susceptibility. Test methods must be applicable to all materials and processes of interest. They must be shown to correlate to service experience. Also there is a need to standardize methodology for analyzing moisture content of fluxes and electrode coatings and diffusible hydrogen in the weld deposit (1991)

METHODS TO ASSESS THE SUSCEPTIBILITY FOR HYDROGEN DAMAGE AND STRESS CORROSION CRACKING (18)

The weldments of high strength alloys are often susceptible to hydrogen or stress corrosion cracking. The susceptibility is related to both welding materials and welding practice. New analytical and diagnostic techniques are needed to determine the susceptibility of a given weldment to environmentally enhance cracking and to better select welding practices (parameters, consumables, preheat and postheat treatments) which reduce the problem (1995)

STANDARDIZATION OF TEST DATA (19)

Need to identify the temperature and strain rate regimes over which material property data needs to be generated to meet all design/fabrication needs. Need to standardize the tests to provide uniform, quality data that can be used in advanced constitutive (materials response) models (1995).

DEVELOPMENT OF WELDABILITY TESTS FOR TRADITIONAL AND ADVANCED MATERIALS (12)

A need exists to develop fundamental understanding of the influence temperature, stress state, and strain rates experienced during traditional weldability testing on quantitative results. It is important to know if such differences versus actual welding conditions influence measured weldability indices. Weldability of advanced materials will be dependent on different weld characteristics (i.e., solidification, liquation or cold cracking). Improved tests need to effectively measure susceptibility to these varying defects. Standardized weldability testing systems, equipment, procedures, data analysis, etc. needs to be established. Weldability data base into which data on advanced materials can be readily incorporated for comparison with traditional materials needs to be generated (1995).

PERFORMANCE VS QUALITY OF SOLID STATE JOINTS (19)

Integration of experimental tests, materials characterization, and NDE techniques that will provide a nondestructive acceptance criteria for solid state joints need to be performed. Bottom-line -- provide us with a standard for accepting or rejecting solid state joints based on performance not just defect vs no defect (1995).

5.3.5 Weld Modeling and Prediction Needs

Present	1995	2000	2005

(a) Advanced Modeling and Experimental Verification

(b) Weld Modeling Studies
(c) Physical and Computational Modeling of Weld Defect Formation
(d) Fundamental Understanding of Weld Defect Formation
(e) Experimental Determination of Constitutive Equations

(f) Numerical Modeling of Residual Stresses

ADVANCED MODELING AND EXPERIMENTAL VERIFICATION TECHNIQUES (19)

In all of the presentations, there was an expressed need for analyzing the material response to the joining process. The numerical codes exist today, workstations have become more powerful, and new schemes for "streamlining" the codes exist. What is needed is linking the technology to the customer with the need. What does not yet exist are the materials property database and the constitutive models. We also need to develop advanced experimental test techniques to verify and baseline the codes. Modeling needs to be directly coupled to experimental verification and materials characterization (1992).

WELD MODELING STUDIES (16)

Of particular interest are models to predict heat flow, fluid flow, solidification, and filler metal/flux interactions. These models are required for process control and for consumables development, but they must be related to real world conditions. These models will also be required for automation of welding processes (1995).

PHYSICAL AND COMPUTATIONAL MODELING OF WELD DEFECT FORMATION (20)

Weldability will not progress as a design parameter until a working knowledge of defect formation is obtained. A "working knowledge" is a basic mechanistic understanding that allows defect prediction based on preweld base metal metallurgy, consumable metallurgy, welding parameters and joint geometry. Two types of defects which cannot be modeled at present are solidification cracks and weld porosity. Physical models are needed from which computational (predictive) models can be developed. A modeling approach, using well behaved binary and ternary alloys, should be developed and verified in a more complex, but behaviorally similar alloy system (1995).

FUNDAMENTAL UNDERSTANDING OF WELD DEFECT FORMATION (17)

Fundamental knowledge base is needed for solidification behavior, interfacial behavior, and defect formation (1995).

EXPERIMENTAL DETERMINATION OF CONSTITUTIVE EQUATIONS (21)

Before any modeling effort can be attempted, it is necessary for the controlling physics to be understood. In the case of modeling mechanical response of joints, the constitutive equations governing mechanical behavior at all temperatures below the liquidus are required. This requires careful, accurate determination of stress-strain-strain rate-temperature-time relationship. Without these data, the best of computer models is doomed to failure (1995).

NUMERICAL MODELING OF RESIDUAL STRESSES IN JOINTS (10)

Thermal expansion mismatches between filler materials and materials being joined will result in residual stresses in the joint at room temperature. The magnitude and distribution of stresses will influence the mechanical properties of the joint. Finite element modeling (F.E.M) is frequently used to calculate these residual stresses. Calculational techniques, results, and limitations of F.E.M. need to be clearly determined and explained.

Appropriate numerical modeling techniques need to be described in detail for the general user. Computer codes need to be described in detail and made available to interested users. This will reduce duplication of efforts, provide more reliable and consistent modeling results, and allow for comparisons (2000).

5.3.6 Mechanics, Fracture Mechanics and Inspection Needs

Present	1995	2000	2005

(a) Standard Test for Fracture Testing of Welds

(b) Second - Tier Mechanical Properties
(c) Effect of Constraint on Fracture Behavior

(d) NDE Method to Determine Severity of Defects

(e) Residual Stress Measurement and Control
(f) Defect Severity Characterization for Improved Productivity
(g) Develop Fracture Procedures for Welded Composites

STANDARD TEST PROCEDURE FOR FRACTURE TESTING OF WELDMENTS (15)

Standard test procedures for fracture characterization of homogeneous materials ignore many of the special problems of weldments. Such problems as defect placement, residual stresses, mismatched strength and parameter definition need special consideration. While the general approach including specimen design and test procedure can be modeled after the homogeneous material test, the special problems of the weldments must be addressed in the standard test procedure to assure reproducibility of results between different laboratories (1992).

INCREASED EMPHASIS ON DEVELOPMENT OF SECOND-TIER MECHANICAL PROPERTIES AND THEIR RELATION TO THE JOINT STRUCTURE AND FRACTURE (12)

Increased need for generation and evaluation of "real-scale" joints.

- thermal experience, residual stress and distortion effects in subsized joints may not be representative of actual joints.

Increased emphasis on developing second-tier mechanical properties

- fracture toughness, S-N and da/dn fatigue data, elevated-temperature properties, oxidation and corrosion behavior.
- development of fundamental metallurgical relationships between the joint structure (as influenced by the joining process) on second-tier mechanical properties.
- Difficulties in generating these properties due to limited quantities and high cost of materials, and concern over investing considerable resources in detailed characterization of experimental materials (1995).

STUDY OF EFFECT OF CONSTRAINT ON FRACTURE BEHAVIOR IN THE TRANSITION REGION (15)

Fracture of ferrous alloys exhibits a transition from a brittle to a ductile character at a temperature referred to as the transition temperature. Prediction of fracture behavior around this temperature is very difficult but is also essential for many applications. The dividing line between a brittle and a ductile fracture is influenced by a factor labeled constraint. When constraint differences occur between the fracture toughness test specimen and the surface being analyzed, the prediction of structural fracture behavior is not accurate. Constraint differences can occur due to thickness change, geometrical difference, material strength mismatch and defect size differences. Until a method to deal with these constraint differences is developed laboratory fracture toughness data cannot be used to predict structural fracture behavior in the transition with any assurance (1995).

NONDESTRUCTIVE METHOD TO DETERMINE THE SEVERITY OF DEFECTS (15)

Many different kinds of defects result from the welding process ranging from porosity to partial penetration welds. The influence of the defect on the fracture and fatigue behavior of the weldment depends upon its severity, that is, to what extend it simulates a sharp crack. Single defects could be judged relative to the sharpness of their tips. Clusters of defects often treated as a single large crack could be less severely characterized as small cracks or simply blunt holes. The severity cannot be judged with present nondestructive methods. With new developments in electronics the task should again be addressed (1998).

RESIDUAL STRESS MEASUREMENT AND CONTROL (16)

Residual stresses have been the subject of study for many years. Control of residual stresses is important due to their impact on cold cracking and on distortion, as well as interaction with service loads. Reliable nondestructive measurement techniques, applicable throughout the thickness and to small, discrete areas of weldments are necessary. Build-up of these stresses during welding as well as the final pattern need investigation. This will permit determination of the effects of weld process and procedure variations on residual stresses and perhaps either minimize them or induce favorable ones in service (2000).

DEFECT SEVERITY CHARACTERIZATION FOR INCREASED PRODUCTIVITY (15)

When the ability to nondestructively characterize the severity of a defect is developed, the opportunity will exist for using this increased productivity. Procedures which require full penetration welds where they are not needed or weld repairs for all defects no matter how they influence integrity are expensive and time consuming. Often a defect is characterized in an unrealistically conservative manner because there is no technology to allow a realistic evaluation of the defect. If defects could be graded more realistically as to their potential for fracture, fatigue crack propagation or crack initiation, design and fabrication could be made more cost effective (2000).

DEVELOPMENT OF FRACTURE PROCEDURES FOR THE WELDMENT COMPOSITE STRUCTURE (15)

The composite structure of a weldment makes the prediction of fracture behavior difficult. Traditional fracture parameters such as K, J, and CTOD uniquely relate the applied loading for a structure to the magnitude of the crack tip stress and strain field and can be used to transfer laboratory test results to the analysis of a structure with a defect. When the structure is a composite with differences in tensile properties, as in the case of a weldment, it is not known whether these parameters still apply in the same way. Before fracture prediction for a weldment can be given a sound basis, the correct way to handle its composite structure must be determined both for deformation behavior and fracture parameters (2000).

5.3.7 Welding and Joining Consumables

Present	1995	2000	2005
(a) Aluminum-Lithium and Composite Fillers			
	(b) Hardfacing		
	(c) Low Cost Titanium Consumables		
		(d) Flux and Electrode Coating Systems	
		(e) High Performance Aluminum Consumables	
		(f) Aluminum Filler Alloy Development	
		(g) Aluminum Consumable for Field Construction and Repair	
		(h) Welding Consumables for Automation and Sensor Control Welding	
		(i) Filler Materials for Ceramic to Metal Joining	
		(j) Expanded Welding Envelopes for High Strength Steel Consumables	
		(k) Specifications that Encourage Better Properties	
			(l) Non-Metallic Filler Material for Joining Unlike Ceramics
(m) Anti-Oxidant Coating			

ALUMINUM-LITHIUM AND COMPOSITE FILLERS (8)

Based on recent findings, the presence of lithium in filler alloys has been shown to serve as a potent weld metal strengthener. Although lithium containing fillers are prone to water pick-up and thus require special care in handling, their potential use for high strength weldments warrants further investigation. Aluminum metal matrix composite filler alloys need to be investigated for unique weld metal properties (1991).

HARDFACING (22)

Welded overlay band process for artillery rotating bands needs research (1992).

LOWER COST TITANIUM CONSUMABLES (9)

Consumables for welding titanium are twenty to forty times more expensive than for HY-80 steel. A potential solution would be to modify joint designs with autogeneous welding processes such as buried-arc GTAW or ESW (1993).

FLUX AND ELECTRODE COATING SYSTEMS (16)

Develop a technology base in the physical and chemical properties of fluxes and coatings. Areas under current investigation include chemical analysis methods, void fraction and sizing, particle size analysis and moisture measurement. Areas needing study include electrical resistivity, melting point and phases present in the slag. The binder system for agglomerated fluxes with nonhygroscopic properties need development. Slag-metal interactions need analysis, as does the effect on such things as particle composition and distribution in the deposit. The final result should be design of flux/coating systems (1995).

HIGH PERFORMANCE ALUMINUM CONSUMABLES - SURFACE PURITY (8)

The surface quality and impurity content of existing commercial filler wires do not provide for optimum weld quality. Hydrated oxides on wire surfaces have been shown to be a primary source of hydrogen leading to porosity in aluminum welds. A surface coating treatment is needed which will protect the wire from moisture pick-up during storage and handling. Also, a simple universal test method is needed which can monitor the surface condition. The presence of large amounts of impurities in commercial alloys, e.g., Fe and Si, result in the formation of large angular primary phases during solidification. A study is needed to determine to what extent impurities affect weld metal toughness (1995).

ALUMINUM FILLER ALLOY DEVELOPMENT (8)

New filler alloys with improved resistance to hot tearing and improved strength are now required. With the welding of new high strength alloys, failures now occur in the weld metal where improvement in welded joint efficiencies must be made. Extensive mapping of alloy composition versus hot tear susceptibility is needed using a laboratory weldability tests which correctly represent true weldability. In particular, an in-depth understanding of the effect of strain rate is needed. Also, it may be more

appropriate to compare alloys in terms of constant penetration rather than constant heat input, particularly for Al-Li alloys with low thermal conductivity. Regarding strength, little is known about the strengthening mechanisms in aluminum weld metal. Understanding these mechanisms and the effect of alloy content will require transmission electron microscopic analysis of the precipitates which form upon weld cool down (1995).

ALUMINUM CONSUMABLES FOR FIELD CONSTRUCTION & REPAIR (8)

SMAW AND FLUX CORE - The weld construction, assembly and repair of structures (e.g., portable bridges or personnel carriers) in remote areas necessitates welding under non-ideal conditions, using limited resources not likely to include inert gases, helium or argon. In these circumstances, shielded metal arc welding must be used, although the resulting welds are typically of low quality. In the past forty years, little attention has been devoted to improving upon the flux and binding composition of aluminum coated electrodes, applying state-of-the-art knowledge of salt chemistry, arc stability and protection from hygroscopic tendencies. Another approach, which may prove to be of universal interest, is the development of a flux core wire whereby sufficient flux is present to protect the molten pool without leaving excess residue for corrosive attack (1995).

WELDING CONSUMABLES FOR AUTOMATIC AND SENSOR CONTROL WELDING (18)

Sensor control of welding processes will require welding consumables with consistent behavior. Develop welding wires and fluxes with consistent metallurgical behavior. Determine the consumable composition ranges which have very stable welding arc behavior. Develop new methods to manufacture in economical manner these new consistent and non hydrophilic welding consumables in batch sizes required for industrial production. Advanced welding consumables for sensor control welding could also utilize specific additions to a wire or flux to monitor a specific process behavior (1996).

FILLER MATERIALS FOR CERAMIC TO METAL JOINING (10)

Ceramic to metal joining is accomplished by using metallic filler materials (brazing). A compilation of filler materials listing properties such as contact angle (wettability) with ceramics, bonding properties with ceramics, and melting temperatures would show what is available and where the needs are for new filler materials. Where needs exist, investigations should be started to find and evaluate filler materials. A compilation will provide a manufacturer with a starting place and may reduce duplication of efforts (1995).

EXPANDED WELDING OPERATING ENVELOPES FOR HIGH STRENGTH STEEL CONSUMABLES (16)

Develop consumables to produce weld deposits whose properties are insensitive to weld metal cooling rate. At the same time reduce sensitivity to cold cracking. This will allow minimal restrictions on heat input and preheat restrictions, not only increasing productivity, but at the same time reducing in process weld monitoring and post weld inspection costs. The use of alloy cored and flux cored filler wires should be useful as both a research and a production tool (1995).

SPECIFICATIONS THAT ENCOURAGE BETTER PROPERTIES (23)

Specifications with minimum requirements encourage mediocrity. Specifications should include a mechanism to pay more for products that produce a net savings, through less preheat or better performance. This will require the benefits to be quantified, e.g. elimination of preheat in ship construction could be equated to an added value of $5/lb of consumable (1995).

NON-METALLIC FILLER MATERIALS FOR JOINING UNLIKE CERAMICS (10)

Non-metallic filler materials will have a higher service temperature, better oxidation resistance, and possibly smaller thermal expansion coefficient mismatches with the ceramics than metallic filler materials. Filler materials must be found that will have similar reaction and reaction spreading properties with each of the ceramics being joined. Similar reaction and reaction spreading properties are required for uniform joint properties. Filler materials need to be developed for joining dissimilar oxide ceramics, for joining oxides to carbides, for joining oxides to nitrides, and for joining carbides to nitrides (2000).

ANTI-OXIDANT COATINGS (24)

Health care costs have created the need for anti-oxidant coatings. Surface preparation can be non-value added activities at a tremendous cost. This research can improve workplace environment (1991).

5.4 Table of Weldability and Joinability Opportunities

I. METALLURGICAL

0-5 Years	Structures/Properties Characterization
3-5 Years	Microstructural Evolution Dissimilar Materials
1-5 Years	Metal/Metal
3-5 Years	Metal/Ceramic
5-10 Years	Metal Composite
5-10 Years	Consumables 1-3 Years $\leq$130 KSI 5-10 Years $\geq$150 KSI >10 Years $\geq$150 KSI, High K_{IC}

II. FITNESS FOR PURPOSE

3-5 Years	Fracture Mechanics Design Acceptance for Simple Materials (Non-Ballistic Applications)
5-10 Years	Heterogeneous Materials
>15 Years	Composites

III. ELECTRONIC MATERIALS - SOLDERING

3-5 Years	Understanding Meaning and Implication of Solder Wettability
3-5 Years	Improved Metallizations
5-10 Years	Lifetime Prediction for Solder Joints
5-10 Years	Improved Solder Alloys Including "Structural" Solders
5-10 Years	Solder Process Monitoring
>10 Years	3-D High Density Designs/Processing

IV. PROCESS RESILIENCY

1-3 Years	Simple Materials
>5 Years	Advanced Materials

V. INSPECTION

3-5 Years	Small Defect Identifiable
5-10 Years	Real Time NDE
>10 Years	NDE of Composite Materials

VI ANALYTICAL MODELING/SENSORS

1-5 Years	Partial Predictive/Measuring Capabilities
>10 Years	Complete Prediction/Data Collection Capability

Lower Priority Issues

VII. ENVIRONMENTAL ISSUES

1-3 Years	Solvent Substitution
3-5 Years	Solvent Elimination
3-5 Years	Lead-Free Solders
5-10 Years	Fume Abatement

VIII. THERMOPLASTICS

3-5 Years	Simple Materials Thin Sections (Manufacture and Repair)
5-10 Years	Sophisticated Joint Designs
>10 Years	Thick Section (Manufacture and Repair)

IX. EQUIPMENT

3-5 Years	Feedback Controlled Solid State Welding Equipment
>5 Years	>5KW Continuous Wave Nd:YAG Lasers
>5 Years	High Power Excimer Lasers

5.5 SCOPES FOR SPECIFIC WELDABILITY AND JOINABILITY OPPORTUNITIES

5.5.1 Weldability and Joinability Opportunities

Present	1995	2000	2005

(a) Use of Water Jet Cutting for Titanium Welds
(b) Thermoplastic Composite - Reduced Manufacturing Costs
(c) Improved Mechanical Performance Thermoplastic Composite
(d) EBW of Titanium

USE OF WATER JET CUTTING FOR TITANIUM WELDS (23)

Use water jet cutting to prepare edge for autogeneous welding. This approach eliminates all solvents and it eliminates all heat affected zone problems from other flame cutting processes (1993).

EBW OF TITANIUM (23)

Use electron beam welding, EBW, for single pass autogeneous welding. This practice will eliminate distortion, fit-up problems, and a variety of other problems associated with other welding processes. Heavy section applications need additional work (1993).

THERMOPLASTIC COMPOSITE-REDUCED MANUFACTURING COSTS (13)

Thermoplastic composites can offer simplified manufacturing processes and reduced manufacturing cost. Also thick sections can be joined.

Short joining times can be experienced with no need for autoclaves. Continuous processes/stepwise process for large structures can be developed.

Process technologies have been demonstrated but at an early stage of development. Joint design technology must be developed. Material weldability data for ballistic structures has not been developed (1993).

IMPROVED MECHANICAL PERFORMANCE THERMOPLASTIC COMPOSITES (13)

Fusion bonding of thermoplastic composites has some significant attributes. These attributes include: loads are distributed uniformly, excellent mechanical performance of joints and improved quality integrity.

Joints have the same properties as the composite. Fiber strengths may be transmitted across the bond line without hand lay up. Surface preparation is less critical and is minimal.

Joints have been made with greater than 80 percent of substrate energy release rates. Process improvement is needed for manufacturing reliability.

Hot/wet properties of welded joints have properties similar to the composite. Shear loadings are preferable to peel for composites in general. This is true for welded joints as well. Polymer morphology in joints is not understood at this time. Techniques for welding fibers across the bond line have been demonstrated but process definition is needed (1993).

5.5.2 Weldability Tests and Analytical Opportunities

Present	1995	2000	2005

(a) Application of Advanced Characterization Technique for Joint Evaluation

(b) Constitutive Equations Relating Welding Processes Parameters and Materials to Weldment Properties

(c) Equal Property Diagrams and Analytical Expressions for Weld Metal

(d) The Concepts and Analytical Approaches of Material Science for Nonuniform Systems

APPLICATION OF EXISTING FITNESS FOR PURPOSE TECHNOLOGY (25)

Fitness-for-purpose procedures for welded structures are currently available. Existing methods contain many simplifying assumptions about the nature of flaws in welded structures. Calculations of critical flaw size are normally very conservative. Despite the conservation, fitness or purpose assessments often lead to very generous flaw tolerances. Adoption of existing fitness for purpose technology by the U.S. welding fabrication will lead to enormous economic benefits (1991).

CONSTITUTIVE EQUATIONS RELATING WELDING PROCESS PARAMETERS AND MATERIALS TO WELDMENT PROPERTIES (18)

There is an opportunity to establish the constitutive equations relating weldment microstructure and properties to welding consumable and base metal compositions and to the welding thermal experience using sound metallurgical and engineering science concepts. Predictive equations based on fundamentally based concepts will allow for a broader ability to predict properties for the engineering alloys and accelerate the selection and use of these new materials (1994).

EQUAL PROPERTY DIAGRAMS AND ANALYTICAL EXPRESSIONS FOR WELD METAL (18)

Diagrams plotting weld metal properties as a function of weld metal composition and welding thermal experience need to be developed. These diagrams will allow for better selection of combinations of welding parameters and welding consumables with variations in welding heat input. These equal property predictions could also be achieved with analytical expressions with composition and cooling rate as independent variables (1995).

THE CONCEPTS AND ANALYTICAL APPROACHES OF MATERIALS SCIENCE FOR NONUNIFORM SYSTEMS (18)

Weldments, with their solidified weld metal microstructure and heat affected zone, are characterized by gradients in composition, microstructure, and properties. The present concepts of materials science are primarily based on uniform systems and there is an opportunity to appropriately modify these analytical methodologies and mechanistic models to allow better prediction of welded and brazed joint properties and chemical and mechanical behavior (1995).

5.5.3 Mechanics and Inspection Opportunities

Present	1995	2000	2005

(a) Application of Existing Fitness for Purpose Technology
(b) Non-Contact Ultrasonics Technologies

(c) Application of Statistical Methods to Low Toughness Zones

(d) Use of 3-D Finite Elements to Predict Residual Stresses

(e) Use of Advanced Technology to Determine Weld Defect Size

(f) Use of Fracture Mechanics Technology to Increase Productivity
(g) Design of Proof Testing Procedures for Welded Vessels

APPLICATION OF ADVANCED CHARACTERIZATION TECHNIQUES FOR JOINT EVALUATION (12)

Spatial resolution of traditional light microscopy is inadequate for characterization of advanced materials - particularly complex joint structures. Analytical electron microscopy is required for structure characterization - structure analysis (BF, DF, TEM), phase identification (micro-diffraction), and STEM composition analysis. SEM, AEM, EDS, EPMA have become readily available as laboratory tools - most graduate programs require training in these techniques. These tools are <u>absolutely required</u> for the effective development of many advanced material joint structure/property/fracture relationships which are required for optimization of joining and post-processing parameters. Utilization of these techniques require special skills for many advanced materials, particularly composites, and for dissimilar material joints. They are also valuable in the investigation of fiber-matrix interactions, diffusion effects across the joint interfaces, fundamental nature of interface structures, etc. (1991).

NON-CONTACT ULTRASONIC TECHNOLOGIES (26)

NIST has developed non-contact ultrasonic testing techniques. Laser, air-coupled, EMAT, and ESAT techniques are becoming available to enhance the NDE of welded assemblies. Air-coupled ultrasonics is broadly applicable, which includes organic composites, plywood and paper products, rubber products and foams, explosives and propellants, and electronic assemblies, including solar panels (1991).

APPLICATION OF STATISTICAL METHODS TO LOW TOUGHNESS ZONES (15)

The complex structure of a weldment presents a variety of fracture behaviors, particularly in the heat affected zone. Fracture toughness in this region shows enormous scatter and is critically dependent on the placement of a defect. Accurate prediction of structural behavior depends upon a method for handling these problems of uncertainty, not only for the fracture property but also for the location and orientation of the defect; this requires statistical modeling. The application of statistics to fracture modeling is developing well. The technology should be advanced sufficiently in three years to begin to apply this to the low toughness regions for weldments (1994).

USE OF 3-D FINITE ELEMENTS TO PREDICT AND ACCOUNT FOR RESIDUAL STRESSES (15)

Residual stresses present one of the biggest problems for the prediction of the behavior of weldment. They complicate attempts to measure and predict both the fracture and fatigue behavior of weldments. Methods are not available to easily measure residual stress in a nondestructive way. Once measured the fracture and fatigue models cannot handle in a reliable quantitative fashion. Advances in numerical modeling will be available in five years to predict the residual stress pattern based upon the 3-D thermomechanical modeling of the welding process. In addition the effect of the residual stresses on the fracture and fatigue behavior can be studied with 3-D numerical modeling of stress and strain behavior for growing defects (1996).

USE OF ADVANCED TECHNOLOGY TO DETERMINE SIZE OF WELD DEFECTS (15)

One of the major unknowns in using a fracture mechanics based approach to determine the integrity of a weldment is knowing the size and severity of defects found in the weldment from a nondestructive test. Advances in the electronic equipment used for NDT and new procedures in the analysis of the data should allow more realistic evaluation of weldment defects. Electronic equipment and computer capability improve by an order of magnitude every few years. In the near future the tools should be available, as well as analysis techniques such as image enhancement and pattern recognition, to allow major advances in the characterization of weldment defects (1998).

USE OF FRACTURE MECHANICS TECHNOLOGY TO INCREASE PRODUCTIVITY (15)

Procedures required to obtain certain strength and toughness properties in a weldment, such as post weld heat treatments can greatly increase the time and cost of fabricating a structure. Redesign of the weldment with the study of the impact on its structural integrity may result in more efficient procedures which still have sufficient strength and toughness. Such things as undermatching rather than overmatching the weld metal or relaxing requirements on toughness may allow higher productivity with no sacrifice in the integrity of the structure. Using existing fracture mechanics approaches to set realistic requirements for strength and toughness could allow a more efficiently designed welding procedure (2000).

DESIGN OF PROOF TESTING PROCEDURES FOR WELDED VESSELS (15)

Proof testing is not a method to estimate the size of defects and to provide a basis for life estimate in pressure boundary structures. The proof test can be used as an alternative or backup to NDT. Present proof test methods can damage the structure resulting in an unreliable estimate of remaining life. In addition the analysis of the proof test may penalize the better material. Proof test procedures could be specially designed for weldments. These procedures would consider the composite structure with differences in strength and toughness as well as types of defects and fatigue growth patterns. A well designed proof test procedure could help with the studies to use fracture mechanics for increased productivity (2000).

6.0 THE WORKSHOP - SECOND DAY: WELD PROCESSING

The second day of the workshop was structured in the same format as the first day; the topic of discussion was the research and development needs and opportunities of welding processes. The morning session identified the needs, utilizing invited speakers for specific processes important to defense manufacturing. The speakers are listed below.

Day Two - Morning: Welding and Joining Processes Needs

NRL Dr. Edward Metzbower	"High Speed Thick Section (Beam) Welding"
CSM Dr. Gerald DePoorter	"Ceramic Joining"
ERC/Ogden Inc. James D. Geis	"Joining of Microelectronics"
EG&G Rocky Flats (IMOG) Dr. Paul Burgardt	"Welding Precision Assemblies"
MTS Corporation Dr. Dawn White	"In Process Inspection of Welding"

These invited speakers also brought prepared material which was distributed and incorporated into this workshop report. The invited speakers led discussions and collected other inputs concerning welding requirements of the Army.

In the afternoon of the second day, the invited speakers introduced three to five specific opportunities to increase weld integrity, increase productivity, and reduce cost from advances in welding and joining processes. These invited speakers also prepared written documents for distribution and inclusion into the workshop report. These invited speakers also led discussions and collected other inputs of new advances in processes. The invited speakers are listed below:

Day Two - Afternoon: Welding and Joining Process Opportunities

INEL Dr. Hershall Smart	"State of Our Physical Understanding of Welding"
Babcock and Wilcox Troy Manley	"PAWS Program"
AWI Dr. Jerry Jones	"Process Control and Neural Control System for Welding"
NIST Dr. Chris Fratunko	"Advanced NDE for Real Time Process Control"
EGG Mounds Eric Johnson	"Statistical Process Control"

A three-member invited panel convened in the evening to make assessment, prioritize, and promote discussion on the specific process needs and opportunities.

6.1 Welding and Joining Processes - Panel Report

Panel Members: Dr. Jim Key - INEL (Leader)
Prof. Tom Eager - MIT
Mr. Don Schwemmer - AMET

The second day of the workshop on "Advanced Science for DOD Application" was devoted to welding and joining processes. Speakers discussed needs and state-of-the-art research in advanced materials, thin and thick sections, high and low energy density processes, physical understanding of processes, automation, and real-time sensing/inspection. Workshop participants prioritized needs and opportunities, i.e. current or developing capabilities and categorized them into near-term (0-5 years) and long-term (beyond 5 years). Panel members collected and distilled participant input constructing the following lists of prioritized needs matched, where possible, against opportunities/capabilities.

NEAR TERM (0-5 YEARS)

Needs	Opportunities
1. Automation	
Process characterization	Advanced diagnostics; physical modeling
Data acquisition	Faster computers; lower costs; advanced software
Controls (process parameters)	Position controls; vision systems, statistical process control
Sensors	Advances in ultrasonic, voltage, and acoustic signal signature analysis
Software	Packages written in high-level languages
Systems integration	Interdisciplinary teams; standardization
2. Real-time NDE (to eliminate radiography)	Noncontact ultrasonic or laser acoustics; image/data processing

3. Advanced processes (special materials)	
Solid state	Friction, diffusion bonding, electrical resistance shape welding, etc.
High energy beam	CW-YAG over 2KW; filler metal additions, specifications
Field repair	(No reported activity)
4. Microelectronics fabrication/ assembly (Process controls-materials-test procedure)	Statistical process control
5. Education - all levels	Textbook; teaching aids; DOE programs
6. Environmental, safety, and health issues	(No reported activity)

LONG TERM (BEYOND 5 YEARS)

Needs	Opportunities
1. Automation-Systems Approach	
Predictive models	Multidimensional physical models; control models/algorithms
Weldment property-based controls	Artificial intelligence, neural networks
Sensors	Advanced noncontact NDE
Advanced Software	Parallel process; fuzzy logic; expert systems
Systems integration	Interdisciplinary teams
2. Advanced processes/special materials	(dependent on unique properties of materials)
3. Microelectronics fabrication	(No reported activity)
4. Education	(Ongoing)
5. Environmental, Safety, and Health	(Ongoing)

Automation was by far the largest priority because it is the enabling technology for many advanced materials applications. Near and long term needs form a continuum of increasingly sophisticated hardware and software. Current needs emphasize building in reliability and quality through capabilities in real-time sensors, simple PC-based controls, and statistical process control. These systems focus more on controlling parameters at this stage than properties. A system approach should be used with emphasis on integration of design, materials, sensors, mechanical and electrical components, and software. Fundamental characterization of processes utilizing an integrated cycle of diagnostic measurement-physical modeling is a necessary prerequisite to any serious attempt at automation, especially intelligent controls. Automation will advance, not only with time and funding, but naturally with increased computer capabilities, parallel processing, neural networks, and other artificial intelligent methods developed for other intelligent processing applications. These advances will allow control of properties as contracted with parameters. A minimum funding level for welding applications should allow use of advances in relevant technology as soon as it becomes available.

Real-time NDE using noncontact transducers is important, not only to replace cumbersome and expensive radiographic inspection but also as sensors for process control. These advancements also form a technological basis for future sensor development.

Advanced processes were coupled with special materials because many joining applications involving special materials may require a unique or new process. Many of these advanced processes will be based on solid state or high energy beam processes that minimize heat input. This advanced process development will be incomplete without development of field repair processes and procedures.

Fabrication of microelectronics into assemblies has a full spectrum of process-materials-testing needs. Although statistical process control is being applied, this application seems to be as deserving of closed-loop control systems as the physically larger applications.

Education is, and will continue to be a need. The two ends of the spectrum-training of manual arc welders and PhD level researchers - are in better shape than the middle of the system which comprises the welding technologist through the BS-level engineer. Textbooks, equipment, materials, especially advanced materials, and educators remain a need with inadequate resources.

Finally, environmental, health, and safety issues are being thrust on federal laboratories, private industry, and educational institutions alike. Research opportunities exist (but were not mentioned in the workshop) in environmentally acceptable processes. These issues should have concurrent emphasis in the curricula of educational institutions.

6.2 Scopes for Specific Needed Processing Projects

The following titles represent the topics submitted by individual participants when asked to contribute their ideas concerning the most pressing needs in the area of welding and joining processes. The titles have been arranged in chronological order. Immediately following the chronological tabulation of titles, the description of needs submitted by individuals, together with title, are presented.

6.2.1 Welding and Joining Process Needs

Present	1995	2000	2005
(a) Welding Ability/Mechanical Properties			
(b) Multipass High Energy Density Weldments			
(c) Joining Techniques for Electronic Materials			
(d) Environmental Concerns in Joining of Electronic Materials			
(e) Hardware Needs for Welding of Precision Assemblies			
	(f) High Energy Density Welding		
	(g) Aluminum Welding Process Development		
	(h) Laser Cutting Systems		
	(i) High Power, CW YAG Laser		
	(j) Process Modeling for Welding of Precision Assemblies		
	(k) Predictive Models		
	(l) Nonlinear Dynamics		
		(m) Reduced Cost of EBW and LW Equipment	
		(n) Military Specifications of High Energy Density Welding	
		(o) Weld Wire Additions for High Energy Density Processes	
		(p) New Materials for Electronic Joints	
		(q) Novel Heating Methods for Ceramic to Metal Joining	
			(r) Elminating Electrical Interconnections

WELDING ABILITY/MECHANICAL PROPERTIES (28)

The information in the literature available to the designer as to the weldability and mechanical properties of high energy density weldments is meager. Thus both an opportunity and a need arise. The need is there because high energy density welding of some alloys results in unacceptable mechanical properties for DOD applications. The opportunity is there because the research community can create the needed data (1993).

MULTIPASS HIGH ENERGY DENSITY WELDMENTS (28)

High energy density welds are invariably autogeneous. Multipass weldments, with and without filler metal, will be required in thick section welding. Porosity at the bottom of the keyhole will be a problem. Non-keyhole welding is a possibility. A great deal of research must be done (1993).

JOINING TECHNIQUES FOR ELECTRONIC MATERIALS (27)

As smaller electrical lead sizes reduce the ability to conduct heat from the chip or provide mechanical support, alternate alloys are replacing brass alloys. Phosphor bronzes and beryllium coppers can meet these more stringent requirements.

Ovens with inert gas shields are able to provide greater control over solder wetting for very fine-pitch devices. For even more sensitive devices, laser soldering in an inert atmosphere is able to avoid the damage that occurs when a component or an entire board is exposed to soldering temperatures. The lower oxidation potential in an inert (or special reactive) atmosphere permits flux-less soldering (1993).

ENVIRONMENTAL CONCERNS IN JOINING OF ELECTRONIC MATERIALS (27)

Lead-free solder alloys exist but need to be fully characterized (mechanical and electrical properties, aging, corrosion, etc.) before they can replace existing solders. The need is immediate, since a bill has been introduced to Congress (S.2637) to limit lead in solder to 0.1 percent within 12 months after it is passed.

Non-chlorinated cleaning fluids for solder boards have been developed, but must be thoroughly evaluated for their effectiveness, and potential detrimental effects on the solder integrity. The Montreal Protocol (ozone depletion concerns) lists deadlines that make this a high priority. These alternate cleaning agents (containing saponifiers or solvents) could have disposal or toxicity concerns (1993).

HARDWARE NEEDS FOR WELDING OF PRECISION ASSEMBLIES (29)

Improved data acquisition and control systems (DAS/CS for GTA and for high energy density processes) are largely available at this time. Process control is largely adequate at this time, but control of the weldments should be improved. Interactive control of weld shape (weld depth and width control) is needed. Real-time NDT for voids, hot cracking and other defects needs more development. Real-time feedback of NDT data for process control is also desirable (1993).

HIGH ENERGY DENSITY WELDING (28)

The introduction of high energy density welding into a production facility is accompanied by several requirements: education, MILSPECS, adaptive control/NDE, reduced costs, weld wire additions (1995).

ALUMINUM WELDING PROCESS DEVELOPMENT (8)

VARIABLE POLARITY - Much success has been achieved using the variable polarity plasma arc process, used for joining 0.5-in-thick inch aluminum plate in the key-hole mode and vertical-up position. The short time interval with DCEP gives the needed oxide cleaning action; the long time interval with DCEN gives the needed penetration; and the rapid switching action (i.e.: square wave form) obviates the need for high frequency arc stability. Further development of this process is needed to fully characterize the effect of process parameters including determining the need for cleaner pulse signals, independent EN and EP current, and superimposed pulsed current. Development of an out-of-position process is another need (1995).

PROCESS CONTROL - The current trend in industry is to develop weld control based upon "blind" statistical analysis of weld data. A better methodology is needed which combines statistical analysis with an analytical analysis based on a fundamental understanding of weld physics and metallurgy (1995).

LASER CUTTING SYSTEMS (27)

The same technology used to melt solder to form joints can be focused to a higher intensity and used to cut materials with a very narrow and precise kerf. It has been applied to the trimming of precision resistors. Such a laser can also be applied to the construction of a very complex device, which has suffered from poor yields. A chip can be constructed with redundant circuit elements. After fabrication, the various circuit elements could be inspected. The laser could be used to interconnect good elements (and cut the leads to any defective or redundant elements) to form a fully functional device (1995).

HIGH POWER, CW YAG LASERS (28)

Solid state lasers can be married to fiber optics and conventional robots to create a welding system. CW YAG lasers of greater power are needed. This is a unique opportunity. The laser engineering must be completed and the utilization of the process must be proven (1995).

PROCESS MODELING FOR WELDING OF PRECISION ASSSEMBLIES (29)

Application of heat flow concepts to fixture and heatsink design is needed. Application of modeling to process and joint design and optimization can increase production yield. Process and heat flow modeling needs to be related to process variables and used for interactive controls (1995).

PREDICTIVE MODELS (7)

Predictive models are needed to support procedure and process development, weldment design, materials development, and process sensing and control. To provide design tools to the welding engineer, predictive models are needed which adequately represent the physics of the welding process, the response of the materials to the process heat, mass, and force inputs, and the resulting thermomechanical response of the weldment (1995).

NONLINEAR DYNAMICS (7)

Nonlinear dynamics needs to be incorporated into weld thermofluids research. Although the effects of nonlinear dynamics on convective heat and mass transport in fluids and plasmas have been recognized for many years, there have been few attempts to extend this knowledge to welding science. Indeed, in a recent international conference on modeling of welding, participants expressed the need to perform research under conditions for which nonlinearities may be ignored, even though it is recognized that most welding processes do not operate under such conditions (1995).

REDUCED COSTS OF EBW AND LW EQUIPMENT (28)

High energy density welding equipment, be it laser or electron beam, is extremely expensive to purchase and costly to operate. A reduction in the initial capital equipment is a definite need in making these processes more competitive (1998).

MILITARY SPECIFICATIONS OF HIGH ENERGY DENSITY WELDING (28)

DOD operates on a system of specifications, commonly known as MILSPECs. Such a specification does not exist for high energy density welding. A recommended practice has been written for electron beam welding by C7 of AWS; a companion recommended practice for laser beam welding has been initiated. A definite need exists for a MILSPEC and recommended practices (1998).

WELD WIRE ADDITIONS FOR HIGH ENERGY DENSITY PROCESSES (28)

For thick section welding with a high energy density process, the addition of weld wire into the fusion zone must be utilized. This technique has not been studied to any great extent, as to either the process or the resulting properties (1998).

NEW MATERIALS FOR ELECTRONIC JOINTS (27)

Conductive epoxies and polymers have been proposed and early versions are now available for joining electronic components. They avoid a fundamental spacing limit in solder joints determined by the physics of wetting and meniscus formation in the lead-tin solder alloys, and the practical limits of application of solder paste. The electrical and mechanical properties and range of application of these fluxless adhesives need to be identified (2000).

NOVEL HEATING METHODS FOR CERAMIC TO CERAMIC AND CERAMIC TO METAL JOINING (10)

Techniques for energy deposition confined to the joint area for ceramic to ceramic and ceramic to metal joining need to be investigated and described for industrial application. In many cases it may be impractical and inefficient to place entire assemblies into a furnace for joining. In these cases the thermal energy for joining must be directed at the joint area. Possible techniques for investigation include microwave heating, Radio Frequency induction heating, laser heating, and electron beam heating. A compilation of methodologies needs to be prepared and made available to all potential users (2000).

ELIMINATING ELECTRICAL INTERCONNECTIONS (27)

Many of the interconnection problems (alignment, wetting, heating procedure, inspection, etc.) occur because we are pushing older technology past its apparent limits. Optical technology would seem to have broader limits, and would seem to be applicable at the chip or device level. Transmission of signals by light avoids metallic interconnections, and offers broader bandwidth and lower power. The connections could be in the form of SiO_2 waveguides on the chip, discrete optical fibers, or diode emitters paired with receivers (2005).

6.2.2 Sensors, Process Control, and Inspection Needs

Present	1995	2000	2005
(a) Statistical Analysis for Process Control			
	(b) Inspection of Electronic Joints (c) Adaptive Control/NDE (d) Material Control for the Welding of Precision Assemblies		
	(e) In Process Inspection Engineering Needs (f) In Process Inspection Electronics Needs (g) In-Process Control (h) Intelligent Control Strategies		
		(i) Resilient Welding Parameters (j) Fully Coupled, Distributed Process Models	
		(k) In-Process Inspection for Alternative Processes and Materials (l) Welding for Serviceability (m) Neural Network for Welding Processes	
			(n) Fully Coupled, Dynamic Distributed Process Models

STATISTICAL ANALYSIS FOR PROCESS CONTROL (24)

There is a risk involved if you choose to combine analytical and statistical analysis methods to develop weld process control. That is, the effort to combine these two systems could be such a difficult task that no results would be generated and no benefits observed. It is recommended that the weld process be qualified via sound analytical methods, then the SPC/design of experiment technique of choice be employed to enhance the robustness of the process. Work is needed to educate how and where to use statistical analysis for process control (1991).

INSPECTION OF ELECTRONIC JOINTS (27)

The imprecision and costs associated with visual inspection of solder joints have resulted in a variety of new inspection technologies. One system is based on laminographic (tomographic) imaging of various planes within a solder joint. It is an autonomous system (automatic board feeder, CAD inspection files, SPC report generator) that can make automatic accept/reject decisions based on solder geometry at ten views per second. Another system uses a laser to measure the cooling rate of solder joints. Within about 100 milliseconds per joint, it can detect various solder joint defects, including poor contact at the interface. A third system uses a structured laser source to measure the profile of solder joints (1993).

ADAPTIVE CONTROL/NDE (28)

Adaptive control and non-destructive evaluation are commonly used with the welding process in order to insure high quality, defect free weldments. However, in the case of high energy density welding, these two techniques are sorely lacking. Little effort has been made to upgrade them so as to be useful in high energy density welding (1993).

MATERIAL CONTROL FOR THE WELDING OF PRECISION ASSEMBLIES (29)

Testing of elemental composition of materials is important for penetration control (oxygen and sulfur in steels). Incoming material certification through chemical analysis and material weldability testing needs to be further established. Testing of material composition is important to control hot cracking and void formation. The role of specific alloy additions need to be identified for many high alloy materials. Control of materials on the shop floor is important in welding precision assemblies. On-the-floor testing of materials, for elements important to weldability could be very useful. Real-time process feedback for material condition is needed (1993).

IN-PROCESS INSPECTION ENGINEERING NEEDS (30)

A number of aspects of inserting advanced sensing technology into welding are associated strictly with engineering issues. The problem of developing miniaturized sensors which do not impede access to joint locations, and which are not so heavy as to hamper robot movement is one example. Another is cabling for data transmittal. Telemetry is one possible solution to excessive amounts of cabling on multiple sensor systems. Transducer robustness is also an engineering issue, which is particularly a problem in welding due to the hot dusty environment and very noisy EMF environment. Image processing is

another issue, in which developing software engineering techniques and algorithms to reduce image processing time will make vision systems far more suitable for real time systems (1995).

IN-PROCESS INSPECTION ELECTRONICS NEEDS (30)

The electronics joining industry has additional needs, such as methods to determine integrity of a very large number of small joints in a crowded space. Some potential methods include x-ray microscopy and infrared imaging. A non-traditional approach would be the use of vibration pattern imaging. In general, this is an important area which has received limited attention (1995).

IN-PROCESS CONTROL (7)

Capability needs to be developed to sense and control all aspects of weld quality during welding. This need requires the development of dynamic models of process physics, materials behavior, and weldment response. In addition, significant advancements are needed in the capabilities of sensors to detect in-process metallurgical structure, materials properties, and defects (1995).

INTELLIGENT CONTROL STRATEGIES (32)

Knowledge Representation Paradigms: In order to develop intelligent control systems, appropriate paradigms will need to be designed. These should take advantage of the latest artificial intelligence technology and be designed to maximize the capabilities of software and hardware systems. These paradigms should clearly separate logic processes from the domain knowledge so that as the body of knowledge changes, system upgrade and maintenance is optimized. The methods of representing knowledge should also operate in an environment in which software and computer/electonics hardware are fully and easily integrated.

Separation of Sensor/Process/Analysis: In the near term, a clear delineation should be made between the software and hardware systems so as to maximize the processing capability of the system. In order to operate intelligent control systems, large quantities of data will need to be processed in short time periods. Interfaces between the software systems and hardware based systems will need to be developed and standardized. Hardware (e.g. VLSI circuits) which are model based and allow the processing of sensor data and process analysis will be needed both for welding and for other manufacturing processes.

Expert Systems Technology: Expert systems of today have significant limitations, a principal one of which is their inability to deal with a dynamic information environment. As we progress to truly intelligent systems, self learning expert system architectures that are robust, can distinguish between good and bad information, and that can un-learn old non-useful information, are needed.

The expert systems application should include engineering/control recommendations capabilities. As the number of engineers in the United States continues to decline through this decade and the number of experienced welding technicians decreases through retirement, we will need expert systems to help with the routine engineering tasks and control strategy decisions in off-line planning/engineering workstation environments (1995).

RESILIENT WELDING PARAMETERS (18)

Often numerous sets of welding parameters have been qualified to achieve the same specific weld and welding process requirements. There exist specific sets of welding process parameters which produce weld properties (physical, chemical, and/or mechanical) that are less prone to in-process variations of the welding parameters. Analytical approaches to determine these more resilient sets of welding parameters need to be developed. These resilient parameters will increase the yield and reduce the amount of weld repair (1997).

FULLY COUPLED, DISTRIBUTED PROCESS MODELS (7)

Fully coupled, distributed models of heat/mass transfer, microstructure/properties development, and the stress/distortion response of weldments need to be developed. Research being conducted in portions of such coupling should be extended to include the full welding/materials/weldment interaction. At present this work requires access to a supercomputer and significant funding. Thus, it should be identified as a long range goal (1998).

IN-PROCESS INSPECTION FOR ALTERNATIVE PROCESSES AND MATERIALS (30)

Similar to the electronics issues, there has been limited effort devoted to the requirements of real time inspection for non-arc welding processes, and for joining of advanced materials. Processes such as explosion welding, inertia welding, ultrasonic welding, vibration welding, high frequency flash butt welding, and resistance welding are amenable to in-process inspection and control; however, with the exception of resistance welding, very limited research has been performed. Because of the cost and criticality of welds in advanced materials and the projected needs for non-traditional processes to join them, research in these areas is needed (2000).

Sensor Fusion and Real Time Data Interpretation

Sensor fusion, the use of multiple sensors simultaneously to draw conclusions about weld quality, which could not be performed by any of the individual sensors independently, is key to more sophisticated in-process inspection and control. However, this will require higher speed data processing, particularly of video images, ultrasonic and acoustic emission data, in order to obtain lumped parameter data based on multiple sensor inputs.

Link Conditions and Defects

This topical need is related to the sensor fusion issue. Today, most sensor techniques describe process parameters (voltage, current and travel speed) or the existence of defects (porosity, cracking, LOP etc.). Generally, conditions can be described at a high rate (MHz), and the occurrence of defects at a low rate (as they occur). Linking conditions which are likely to produce defects with actual defect occurrence require both high update rates and the ability to perform sensor fusion. Some fertile research areas include very high frequency monitoring of voltage and current, and high frequency measurements of puddle vibrations since these responses are related to actual

droplet events, and changes in them which may be associated with defect formation.

Advanced Composites Inspection

Both fiber and matrix conditions must be observed, including fiber integrity, and limited work has been done in this area. In order to accomplish this task, particularly in the metal matrix composites (and especially with continuous fibers) novel techniques are required. One example is new work in investigating the use of "optical fibers" in inspecting MMCs through the use of ruby fibers and laser fluorescence. This work is in its earliest stages, and it is desirable to consider its extension to welding and joining.

Interface Conditions

Not only welds in composite materials, but all welds in general can be viewed as composite materials, and interfacial effects are very significant. The DOE recently emphasized the importance of interface science in understanding welding. Some of the application areas of interest to the Army affected by these effects are advanced materials, particularly for armor. Interfacial issues are also of concern in understanding joining in electron, optical and magnetic materials.

WELDING FOR SERVICEABILITY (29)

Process controls need to be further developed to optimize microstructure, to minimize part distortion, to optimize HAZ properties, and to optimize residual stresses. Part and joint design to optimize inspectability of finished part also needs development. Design of interactive controls to optimize part serviceability is needed (2000).

NEURAL NETWORKS FOR WELDING PROCESSES (32)

We do not yet understand the internal operation of these artificial neural systems, however. Thus, mathematical models of these systems need to be developed so that as empirical data is used to create neural network models, the underlying scientific principles can be derived and better understood (2000).

FULLY COUPLED, DYNAMIC DISTRIBUTED PROCESS MODELS (7)

A fully coupled, dynamic distributed model of heat/mass transfer, microstructure/properties development and stress/distortion response of weldments is needed. It is recognized that this need is a wish list item, that is not realistic to achieve until significant advances in computational power become available at reasonable cost (2005).

6.3 Scopes on Processing Opportunities

The following titles represent the topics submitted by individual participants when asked to contribute their ideas concerning the most pressing opportunities in the area of welding and joining processes. The titles have been arranged in chronological order. Immediately following the chronological tabulation of titles, the description of opportunities submitted by individuals, together with title, are presented.

6.3.1 Sensors, Process Control, and Inspection Needs

Present	1995	2000	2005
(a) PAWS - Goals to be Achieved			
(b) Current Computer Architectures			
(c) Control Multiple Axis Manipulators			
(d) High Quality and Productivity			
(e) Effective Hardware Procurement Contracting Using SPC			
(f) Welding Equipment Design Using SPC			
(g) Design for Manufacturability Using SPC			
(h) Continuous Improvement for Welding Processes Based on SPC			
	(i) Offline Programming Capability		
	(j) Operator Interface		
		(k) Motion Control Capability	
		(l) Weld Process Control	
		(m) Parameter Logging	
		(n) Sensor Interactions and New Sensors Technologies	
		(o) Welding Process Development	
		(p) Welding Production and Development Supporting SPC	
		(q) Welding Equipment Calibration Using SPC	
		(r) NDE Benefits Using SPC	
		(s) Joining of Microelectronics	
		(t) Processing Opportunities	
		(u) High Energy Density Welding	
		(v) Welding Procedures	
		(w) Neural Network Architectures	
			(x) Neural Network for Welding Processes
			(y) Sensing and Modeling of Microstructure and Properties
			(z) Portability and Minimal Setup
			(aa) Concurrent Design
			(bb) Hierarchical Intelligent Control Systems
			(cc) Computer Integrated Engineering/Planning/Control
			(dd) Multi-Purpose Sensors and Real Time Feedback (19)

PROGRAMMABLE AUTOMATED WELDING SYSTEM (PAWS) (31)

GOALS TO BE ACHIEVED (1991)

Based on the current and near term available technologies future automated welding systems should have the opportunity to be defined by a set of goals that include:

- Built-in quality
- In-yard capability
- Reduced skill demands
- Increased productivity
- Provide records and traceability
- Increased capability to weld emerging materials

CURRENT COMPUTER ARCHITECTURES (31)

Currently the computer architectures of choice are the UNIX workstation and the OS2 personal computer. These system components can be interfaced to advanced high speed multi-processor controllers for robot system and welding system control. A typical architecture would include a VME bus and multiple 68040 processors (1991).

CONTROL MULTIPLE AXIS MANIPULATORS (31)

Future automated welding systems will have the capability to control multiple axis manipulators (1991).

HIGH QUALITY AND PRODUCTIVITY (31)

Future automated welding systems will have the capability for applications with high quality and productivity requirements (1991).

EFFECTIVE HARDWARE PROCUREMENT CONTRACTING USING STATISTICAL PROCESS CONTROL (33)

DOD has in the past concentrated on inspection of product for conformance to stated requirements with the emphasis on identifying defects. This limited vision of quality attempted to stop defective products from being accepted, but did not address the inefficiency and cost of quality (scrap, rework, repair) that resulted. Today, oversight is being changed from product inspection to increased emphasis on monitoring the controls of processes and ensuring achievement of results while limiting specifications and performance requirements. As a result, contract language is now evolving toward continuous improvement and defect reduction (1991).

WELDING EQUIPMENT DESIGN USING STATISTICAL PROCESS CONTROL (33)

Statistical process control techniques can be used to quantify the stability and capability of welding equipment. Accuracy and repeatability can be easily determined for any welding system. This data can be used to: determine capability of present equipment, design specifications for new equipment, and measure improvements to existing equipment. Efficient maintenance and calibration programs can be based on SPC programs. Capable equipment can be specified to match production applications (1991).

DESIGN FOR MANUFACTURABILITY USING STATISTICAL PROCESS CONTROL (33)

Design for manufacturability assumes capable production processes. This is not possible without SPC to insure stability. SPC is a proactive quality tool which yields necessary information to optimize design of products, equipment, and processes. SPC is an important step on the road to total quality (1991).

CONTINUOUS IMPROVEMENT FOR WELDING PROCESSES BASED ON STATISTICAL PROCESS CONTROL (33)

Statistical process control defines the capability of a process as it is currently configured. Continuous improvement of a system is the reduction of variation in that system. SPC can be used to identify sources of variation so that research and development activities can support production's needs. SPC can measure the effect of improvements with great speed and efficiency. Continuous improvement decreases costs by forever increasing productivity (1991).

OFFLINE PROGRAMMING CAPABILITY (31)

Advanced future welding systems will have the capability to include offline programming capability. Such systems should include motion planning and simulation, collision detection, sensor control planning, and weld model planning (empirical, procedure checking, graphical representation) (1993).

OPERATOR INTERFACE (31)

The operators interface should include on-line programming capability, a windows based graphical users interface, monitoring of the welding process, post-weld analysis (for SPC, and trending analysis), limited operation for changing position, travel speed, and weld parameters (1993).

MOTION CONTROL CAPABILITY (31)

Future systems should have, as a minimum, the capability for path control, path memorization, (electronic) touch sensing, coordinate transformations (e.g. work piece to robot world or to positioner), and should be manipulator independent (1995).

WELD PROCESS CONTROL (31)

Future automated welding systems should offer process monitoring, power supply control, peripheral device control, and through-arc sensing (1995).

PARAMETER LOGGING (31)

For purposes of post-weld analysis and SPC as well as for archival retrieval and analysis if defects are detected later in-service, future automated welding systems should provide a mechanism for monitoring welding parameters and logging the weld history. The logging system should be programmable, and include time, events, positions, frequency of occurrence, value averaging, and a post-weld analysis capability (1995).

SENSOR INTERACTIONS AND NEW SENSOR TECHNOLOGIES (31)

Sensors currently under development that can be applied in the early 1990's include (1995):

- Weld Joint Vision Sensor
- Arc Hydrogen Sensor
- Plateborne Acoustic Emission Sensor
- Through-the-Arc Sensor
- Integrated Optical Sensor
- Electro-magnetic Acoustic Transducer Ultrasonic Sensor
- Arc Signal Monitor Sensor
- Weld Acoustic Sensor

WELDING PROCESS DEVELOPMENT (31)

Future automated welding systems should have testbeds for developing and evaluating various welding processes (1995).

WELDING PRODUCTION AND DEVELOPMENT SUPPORT USING STATISTICAL PROCESS CONTROL (33)

A process that runs in a state of "statistical control" has many advantages to manufacturers and customers. The process is predictable with a measurable capability. It is a stable process which has predictable costs and quality standards. Productivity is maximized and costs minimized because the system has been optimized to its current configuration. The effects of system changes, intentional and unintentional, can be measured quickly and efficiently. Stable processes promote realistic product specifications and production requirements which maximize productivity and customer satisfaction (1995).

WELDING EQUIPMENT CALIBRATION USING STATISTICAL PROCESS CONTROL (33)

The intention of welding equipment calibration is to quantify process measurement accuracy and repeatability. EG&G Mound Applied Technologies has developed a Process Measurement Assurance Program (PMAP) which is based on SPC techniques. The PMAP program quantifies: accuracy or measurement bias, uncertainty or repeatability, consistency over time, and the measurement capability. The PMAP system also helps describe when and how system adjustments should be made. Calibration limits and intervals can be defined with statistical based confidence (1995).

NONDESTRUCTIVE EVALUATION BENEFITS FROM USING STATISTICAL PROCESS CONTROL (16)

The "Key Weld Quality Indicators" are defined by nondestructive testing criteria in Product Specifications. Statistical process control can be used to predict, monitor, and control inspection processes by defining the process capability or confidence limits. Predictable and stable inspection of welded components maximize productivity and decrease cost. SPC can be used to qualify NDE equipment, processes, and operations (1995).

JOINING OF MICROELECTRONICS (37)

Process controls relevant to failure mechanisms are advancing. Experimental work performed in the Solder Technology Program confirmed that x-ray diffraction techniques could detect the presence of key intermetallic compounds, below and covered by a solder coating, and could distinguish between relatively thicker/thinner intermetallic layers. A thrust of the Program now is to further that work by configuring equipment of suitable design and validating its performance as an in-process monitoring and quality control technique in a microfactory environment. Soldering, brazing and welding are all dependent on the inter-diffusion of metals to produce mechanical joining of appropriate integrity. Methods of detecting and monitoring the unique alloys formed during the inter-diffusion process provide a means of quantifying "bonding". This directly supports statistical process control approaches to manufacturing technology and serves to reduce or eliminate visual and/or other methods which are only inferential (1995).

PROCESSING OPPORTUNITIES (7)

Significant reduction in computing hardware cost will soon be seen. Very high level software tools for modeling activities by welding engineer will be available. Dynamic models of pool/bead geometry and predictive models of defect development will soon be available (1995)

HIGH ENERGY DENSITY WELDING (28)

Several opportunities exists: weldability/mechanical properties, multipass weldments, high power, CW YAG (1995).

WELDING PROCEDURES (31)

Future automated welding systems will have the capability to develop and maintain welding procedures (1998).

NEURAL NETWORK ARCHITECTURES (32)

Sensor Data Processing

The application of truly adaptive control systems requires the increased use of sensors to make automated systems more tolerant of their environments. Three of the most pressing problems facing the welding community today in the application of advanced sensor technology are: The ability to operate in the noisy environments typical of manufacturing and field applications. Advanced sensors require much greater throughput of data in order to be truly useful. Systems must move away from single or simple dual sensor control and move to property control as defined by many different simultaneous sensors (1998).

Noise Tolerence: Artificial neural networks are an attempt to implement neural reasoning by using computerized biological neural network architectures. While a true implementation of biological neural network functioning will be many years into the future, current implementations of artificial neural networks exhibit many of the attributes of biological nets. One of the most useful of these, in the manufacturing environment, is the

ability to function in the presence of large amounts of noise. Implementing artificial neural systems quickly in welding automation will serve to accelerate the ability to utilize many sensors now not effectively applied. For example, much work is currently being done, at great expense, to illuminate the weld area with a laser system and then filter out all of the other wavelengths of light except for that of the laser. This is done to remove the great variability of lighting and improve the signal-to-noise ratio. This adds additional bulk to the sensor making it nearly unusable in many automated situations and substantially increases the cost. Utilization of sensor data processing which is more noise tolerant could reduce the need for the cost and extra bulk of this sensor (1998).

<u>Parallel Processing:</u> While there are continuing to be incremental increases in processor speeds, there is a theoretical limit to the speed of a single processor. Eventually it will not be possible to further increase the speed of processors, at any cost. Consequently, the application of sensors that require very high speed processing will necessitate the use of parallel processing architectures. But the move from single (or small numbers of simultaneous processors) to truly parallel processing environments has proven to be quite difficult. It is not always easy (or even possible) to develop parallel processing approaches for some applications. Artificial neural systems offer an advantage over conventional programming in that they are inherently a parallel processing environment. Early implementation of neural networks for sensor data processing, and other highly processing intensive activities, is necessary for adaptive systems to operate to the full potential of capability (1998).

<u>Sensor Fusion:</u> The ultimate goal of any intelligent or adaptive system is to control the process to the quality parameters desired in the finished product. Many sensors are currently available, or are being developed, for welding. Each of them provides a portion of the information necessary to obtain a cognizant view of the quality of a weld. Consequently, in order to determine the quality (e.g. strength, toughness, penetration, defect configuration, etc.) of a weldment and to control it in real time, it will be necessary to fuse together the information from several sensors simultaneously. This problem of "sensor fusion" is difficult to achieve and even when it has occurred in limited applications, it is very processor intensive.

The artificial neural system architecture, just as with the biological analogy, provides a simple mechanism for sensor fusion. Just as the human welder simultaneously combines the sounds, sights, smells, and "touch" (e.g. temperature, etc.) of a weld easily, an artificial neural system can operate in the same manner. Thus, the early implementation of sensor data processing systems as neural networks will provide a much more rapid and cost effective implementation of new and advanced sensor technology to "smart" welding (1998).

<u>Off-Line Planning/Engineering</u>

In order to more effectively utilize adaptive/intelligent welding systems, particularly for few-of-a-kind applications, it will be necessary to substantially increase the capability of off-line planning/engineering systems to reduce the time and cost associated with applying automation. Engineering decisionmaking is often a complex task that requires the application of highly

non-linear and interrelated process models. Expert systems will need to be improved and have the ability to learn from past mistakes in order to be usefully applied in the dynamic manufacturing environment of the future. Finally, much engineering data is in the form of graphic, pictorial, and analogical knowledge. It will be increasingly necessary for engineering/planning workstations to have large scale data systems capable of storing and retrieving this type of data. These systems will need the ability to operate with graphic data knowledge content addressable information (1998).

Expert System Replacement: Expert systems, in order to provide the capability of modelling the complex, non-linear, and interrelated welding process, will need to have artificial neural systems which provide that type of modelling ability. Neural networks have demonstrated the ability to model the welding process despite the lack of a basic scientific understanding of the processes operating in arc welding. In addition, neural networks can provide the ability for expert systems to "learn" and modify themselves as the knowledge of the welding process changes with time (1998).

Fuzzy Logic Implementation: Truly intelligent systems need the capability to make relative decisions. This requires that alternatives be weighed and judged to make the most appropriate decision. For example, the best preheat temperature from the standpoint of hydrogen damage may be too high for a quenched and tempered steel. In this case, a welding engineer would weigh the potential for hydrogen contamination against the potential metallurgical damage done by excessive pre-heat temperature to the base metal and a "best choice" decision would be made. The mechanism for implementation of this type of decisonmaking is Fuzzy Logic. Artificial neural systems offer an opportunity to provide the system with certainty values and fuzzy set membership functions based on net output values. Thus the implementation of neural networks will allow off-line planning/engineering systems to implement intelligent trade-off analysis and improved decisionmaking (1998).

Data Content Based Data System Retrieval: Data used by welding engineers is often not simply numerical in nature, but is often grapical or analogical. Examples are, metallurgical CCT diagrams or microstructure photographs. This information can be stored in data systems as bit-maps or a vector based graphics, but it must have associated with it code names or numerical data to be retrieved. To be useful, it is becoming increasingly important to be able to retrieve data based on the characteristics of the data itself. Artificial neural systems have the ability to provide associative memory and theoretically could be used as the basis of a system for retrieval of graphical data based on the knowledge content of the data (1998).

Welding Process Modelling: Welding models require highly complex, non-linear transformations. But, since the process itself is not well understood, it is often not possible to develop a mathematical formulation of the necessary model. Artificial neural systems are inherently complex non-linear transformations. As a consequence, in the short term, neural networks offer an ideal method for developing models of welding which can transform the process parameter values into quality parameters (e.g. voltage, current, and travel speed can be transformed into weld bead shape, size, penetration, and appearance).

NEURAL NETWORKS FOR WELDING PROCESSES (32)

Several opportunities exist: weldability/mechanical properties, multipass weldments, high power, CW YAG (2000).

SENSING AND MODELING OF MICROSTRUCTURES AND PROPERTIES (7)

Sensors for in-process measurement of microstructure and properties and dynamic models of microstructure/properties and stress/distortion will be available within ten years (2000).

PORTABILITY AND MINIMAL SET-UP (31)

Automated welding systems in the year 2000 should have the capability for portability and have minimal set-up requirements (2000).

CONCURRENT DESIGN (31)

Future automated welding systems should have concurrent design tools available and integrated into the system (2000).

HIERARCHICAL INTELLIGENT CONTROL SYSTEMS (32)

Layered Control: In the near term (i.e. next 5-8 years) there will not be sufficient processing power to develop completely software based intelligent control systems. Parts of the systems will need to be hardware based and embedded into control systems. A strategy for doing this is to layer the control system. A layered design would have the short term feature (i.e. micro/millisecond response requirement). All hardware would be based on using the new generation VLSI technology described above. The medium term control (i.e. 100 - 1000 millisecond response requirement) to make set point changes based in trends in sensor data will need to be software/hardware hybrid with implementation and integration strategies. Finally, the long term control (i.e. seconds to interpass) will need to be software based using intelligent modelling of processes integrated to sensor models.

Application of Appropriate Technology: Dividing the control system into the three time ranges described above, the types of technologies that need to be further developed are: Long Range -- Frame based production rule and semantic network systems that have completely integrated large databases for information and model referral and look-up table access. Medium Range -- Conventional and neural system software integrated into hybrid systems with hardware. One of the major tasks will be to do sensor fusion and to make intelligent decisions regarding the current state of the process. Short Range -- Hardware based systems which have highly complex non-linear process models incorporated for making short term decisions regarding keeping the system at the most optimum process parameter values. These systems will need to be able to decide where, within a set range, to maintain, or change, the process parameter values. Speed will be of the essence with some decisions (e.g. voltage/current fluctuations) needing to be made in microseconds. Consequently, the requirement for welding specific electronic hardware as described above will be met by application of high speed digital signal processors now being designed (2000).

COMPUTER INTEGRATED ENGINEERING/PLANNING/CONTROL (32)

Standardization: Just as standards such as the 5.25 in. and 3.50 inch disks or the ASCII code for alpha/numeric characters or the IGES CAD data standard have revolutionized the computer industry, standards will serve to revolutionize the welding/manufacturing industries. CNC machine codes have been standardized and as a consequence off-line CAD systems of all types can produce plans for automated machining centers. Standards need to be established for software, hardware, and interfaces so that automated welding centers can be fully incorporated into the CIM environment. Standards should be established through the existing ANSI/AWS system of consensus committees.

Specifically, the types of standards that need to be established are:

Software: Establish modular software systems standards so that subprograms from one vendor can be incorporated into central engineering/planning/control systems (e.g. the IMSL Library).

Hardware: Electronics for hardware implementation of intelligent systems should be standard. For example, all welding hardware should communicate using standard computer parallel or software (e.g. RS232) communications or 0 - 10 volt analog control signals (2000).

Interfaces: The interface data systems that communicate between off-line planning/engineering workstations and workcells, between sensors and control systems, and between CAD/CAM software and welding systems, need to have established standards (2000).

Off-line Intelligent Engineering/Planning Systems: These systems developed for welding will not drive the computer industry or the CAD/CAM/CIM industry. As a consequence, welding systems need to be developed that are compatible with these existing systems. These systems will need to have methodologies to incorporate CAD information, include large scale data systems so that engineers can operate in a paperless environment. That will also mean that the publishers of welding related information will need to help and cooperate (e.g. U. S. Government -- mil. specs., ASTM, AWS, ASME, AASHTO, API, etc.) Intelligent systems (i.e. expert systems and blackboard structures) need to be developed to do all of the routine engineering/planning so that the few remaining engineers and experienced technicians can be freed to do more creative work. Finally, these systems will need to have extensive simulation capability to reduce the amount of shop downtime resulting from change-over and robot planning. This simulation software should be fully integrated with the remainder of the engineering/planning software (2000).

MULTI-PURPOSE SENSORS AND REAL TIME FEEDBACK (19)

New computer chips are being developed to process full-field images in real time at the speed of a CRAY-1 computer within a workstation framework. How can this technology be transferred to the welding community?

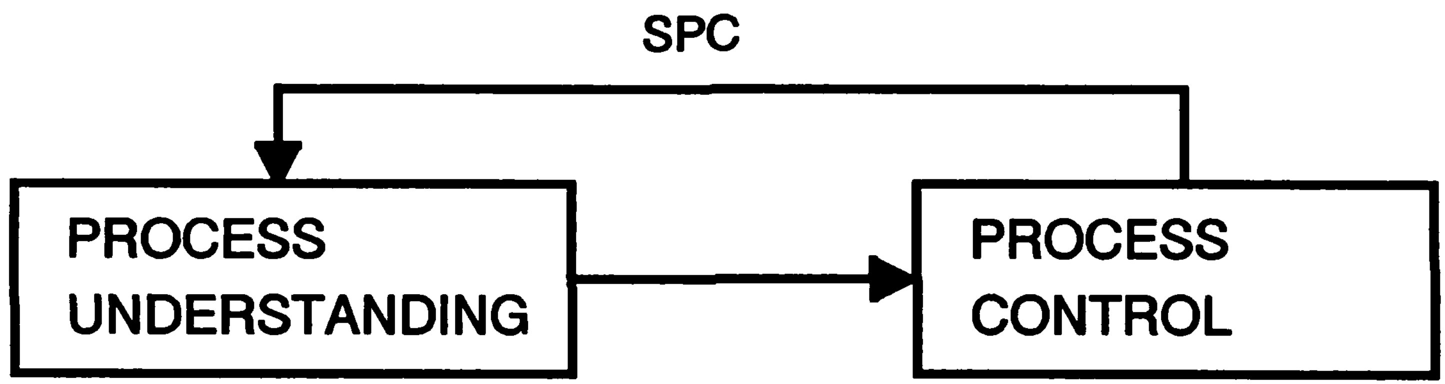
With these types of chips, we can also use multi-purpose sensors which can provide a variety of information in a single measurement. IR thermography is an example of a sensor that can be used for full-field video imaging (for seam tracing and bead shape control), full-field temperatures, measurement of

penetration as a basis of radiance, and measurement of contamination (oxide formation and change in emissivity) (2000).

HIGH ENERGY DENSITY WELDING (28)

Several opportunities exist: weldability/mechanical properties, multipass weldments, high power, CW YAG (1995).

Table II TRAINING FOR STATISTICAL PROCESS CONTROL



Physical Models	Control Models
Fitness for Purpose	Sensors
Prediction of Defect Formation	Standardization/Specification

7.0 EDUCATION AND TRAINING

7.1 Scopes for Education and Training Needs

EDUCATION (28)

Education is by far the most critical issue that accompanies the introduction of a high energy density process into the manufacturing environment. Assuming that the welding engineers are knowledgeable about the process, it is imperative to involve the designers, manufacturing engineers, operators, technicians, foremen etc. in a learning program about the advantages and disadvantages of the process.

WELDING TECHNOLOGIST TRAINING (29)

Precision joining of the future will require a new type of welding operator/technologist with the ability to understand and deal with a variety of issues. These issues include safe and environmentally sound practices, procedural understanding and compliance, attention to details of measurement and recording of data for all welding variables, procedure compliance, environmental compliance and all other process details, basic knowledge of welding fundamentals, vacuum technology, electronics, DAS/ICS fundamentals and a wide range of advanced welding topics is needed. Training of the welding technologist is a challenge for the future success of <u>all</u> advanced welding processes and processing facilities. Training of the technologist of the future to deal with the wide range of issues confronting manufacturers is essential.

DOE and the American Welding Society are initiating a national training facility for the technologist with students and participation coming from all U.S. industry, agencies and individuals. This type of training effort needs to be expanded to guarantee a work force capable of using the advanced welding and joining system being developed (1993).

TRAINING FOR STATISTICAL PROCESS CONTROL (33)

Training is needed at all levels to fully use statistical process control with system integration. See Table II.

FUNDING FOR GRADUATE EDUCATION (36)

As welding and joining technology becomes increasingly sophisticated, the need for advanced degreed scientists and engineers will intensify. Current costs for graduate-level engineering education are approaching $60,000 per year per student. Yet, funding agencies are, at best, maintaining a funding level established in the 1970's. Government laboratories and industry look for the federal funding system to provide them with the scientific and engineering talent, but funding at NSF and similar agencies is completely inadequate to meet the need. All the organizations which require highly trained personnel must begin to accept the responsibility for funding the training, and an appropriate infrastructure for funding graduate-level research and education in welding and joining needs to be established.

8.0 DAY THREE: GENESIS OF A MICROFACTORY

The search for effective ways to introduce new concepts, materials, processes and practice in the most rapid fashion to the defense manufacturers was the main topic for the third day of the workshop. The use of the "microfactory concept" was explored.

8.1 Defense Microfactory Concept: Dr. Phillip A. Parrish, V.P. Advanced Materials Manufacturing, BDM International, Inc., Arlington, VA 22203

Objectives

Accelerate technology transfer of welding and joining to R&D into production for Army systems and subsystems.

Testbed for demonstration projects involving interdisciplinary teams focused on major problem areas.

Training and production personnel (teaching factory)

Development of standards/testing procedures.

Provide action teams and consultants to Army Project Offices for specific high priority problems associated with welding and joining.

Give Army MANTECH program a voice in defining basic and applied research needs to be supported by ARO and Army Labs.

Customer Oriented Goals

Customer - Army Projects Offices (e.g., M-1)

Goal - Develop affordable, cost effective solutions for significant production joining problems on Army systems (generally 6-12 month efforts). Based upon insertion of new and/or available technologies. It should be accompanied by effective training of production personnel.

Customer - Army Manufacturing Technology Program

Goal - Step-function upgrades in welding and joining practice across Army systems: Designs, equipment, controls, consumables.

Customer - Army Manufacturing Science Program (ARO, Labs)

Goal - Emphasis on development and demonstration of: in process quality monitoring and control concepts - concurrent engineering concepts, other interdisciplinary research.

Examples of Interdisciplinary Approaches

Intelligent Processing of Materials (IPM)

- Process Modeling
- In-Situ Sensing
- Adaptive, Nonlinear Process Control Methods

Design, Prototype, and Demonstrate New Welding Systems

Concurrent Engineering

- "Tiger Team" approaches for design involves expertise in traditional component design with expertise in manufacturing, testing, maintenance and repair.

Multidisciplinary teams to be from academic, industrial and other sources.

Should involve students, junior production staff in order to educate, establish new methodologies in future production.

BACKGROUND OF IPM PROGRAM

- USA Spends Millions Developing Advanced Materials
  - Composites
  - Single Crystals
  - Ceramics
  - Fibers
  - Intermetallics
  - Semiconductors
  - High Strength Steel
  - High Temperature Aluminum
  - Magnetic Alloys
- R&D Successes Very Difficult to Translate into Production
- Materials Supply & Equipment Businesses Increasingly Dominated by Foreign Sources

Virtual Factory Concept

GOAL: Play out IPM Process Control Scenarios in BDM Office/Lab Facilities.

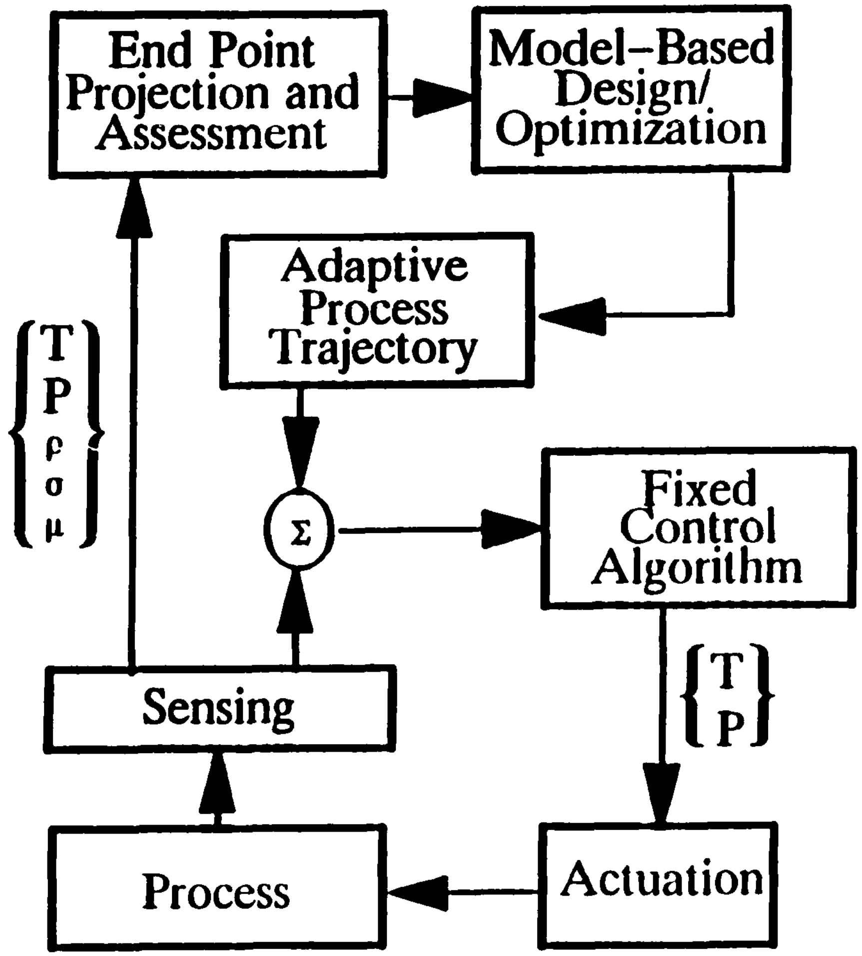
METHODS: Develop and Integrate Component Models in Flexible Simulation Environment.

Interface to PLC and Data Acquisition HW.

REASONS: Difficult to Take Equipment off Line

Need Testbed for Control Approaches

Allows Rapid Development and Qualification of HW Interfaces



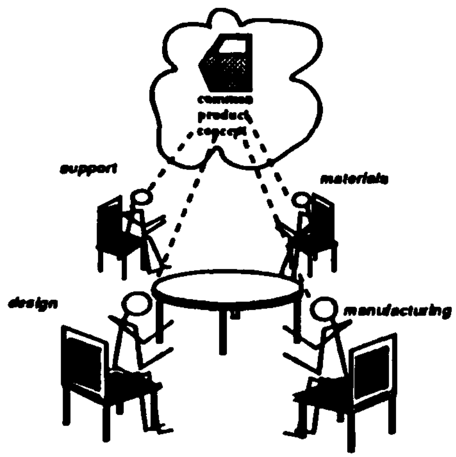
Product Development

DICE

Today

"tiger team" approach (small organizations)

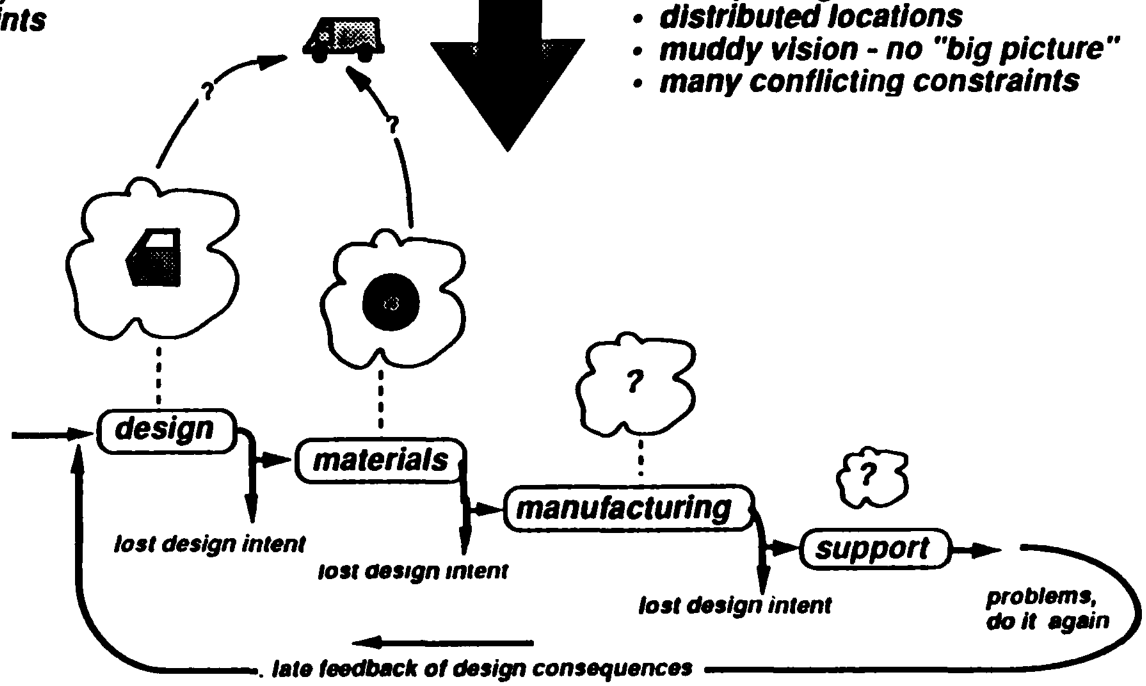
- no organizational barriers
- single location
- single vision (geometry)
- few conflicting constraints



- works well for small enterprises

"assembly-line" approach (large organizations)

- multiple organizations
- distributed locations
- muddy vision - no "big picture"
- many conflicting constraints



- missed expectations
- <u>LONG</u> product development cycles

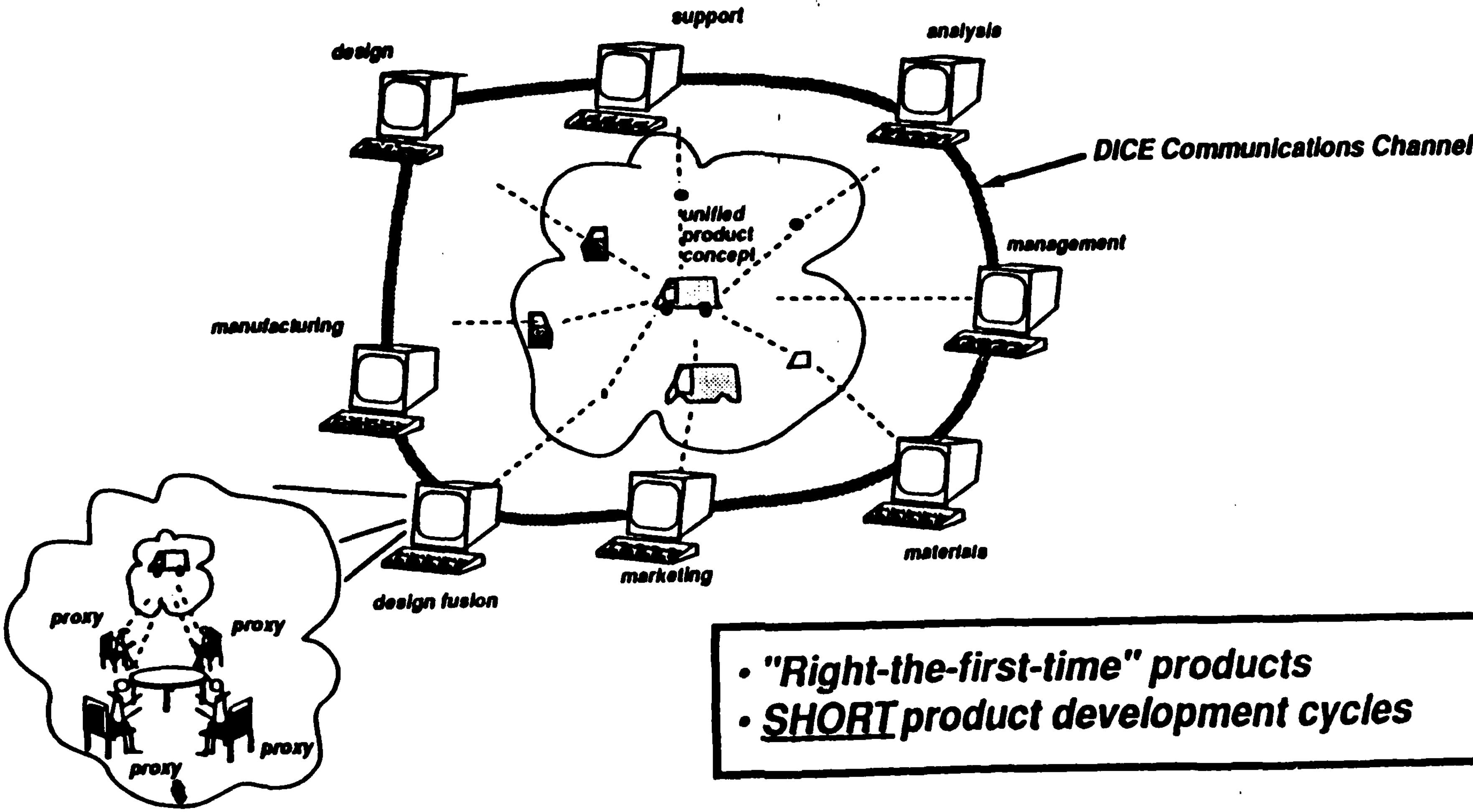
3/14/89

Product Development

DICE

Using DICE

- ***Virtual "tiger team" for large organizations***
- ***Networked co-location***
- ***Unified vision***



- ***"Right-the-first-time" products***
- ***<u>SHORT</u> product development cycles***

System Description

DICE

A Virtual Tiger Team for Large Organizations

Shared Information Model (PPO)

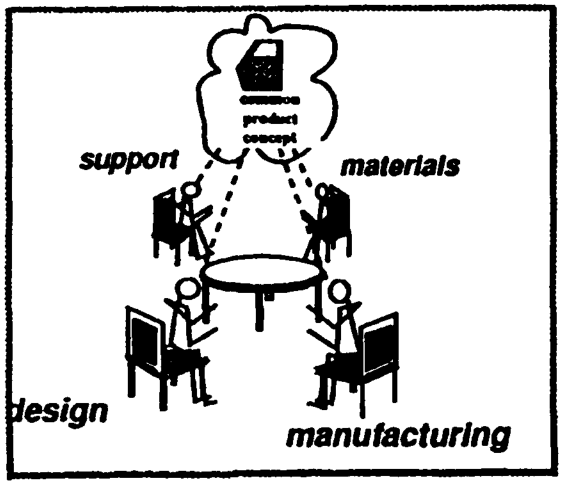
- *Product - Process - Organization*
- *Version and iteration control*

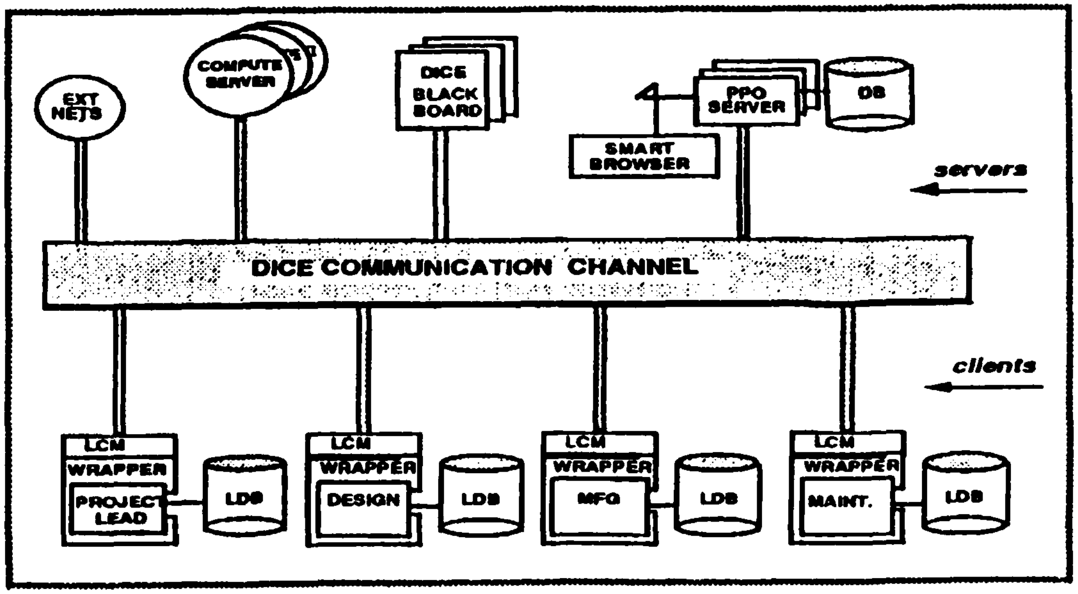
Information Management Framework (Architecture)

- *Concurrent/cooperative work*
- *Progressive refinement*
- *Application wrappers*

Services and Tools

- *Conceptual design evaluation*
- *Resource, feature, constraint & risk management, and optimization*
- *Decision aids, planning, scheduling*





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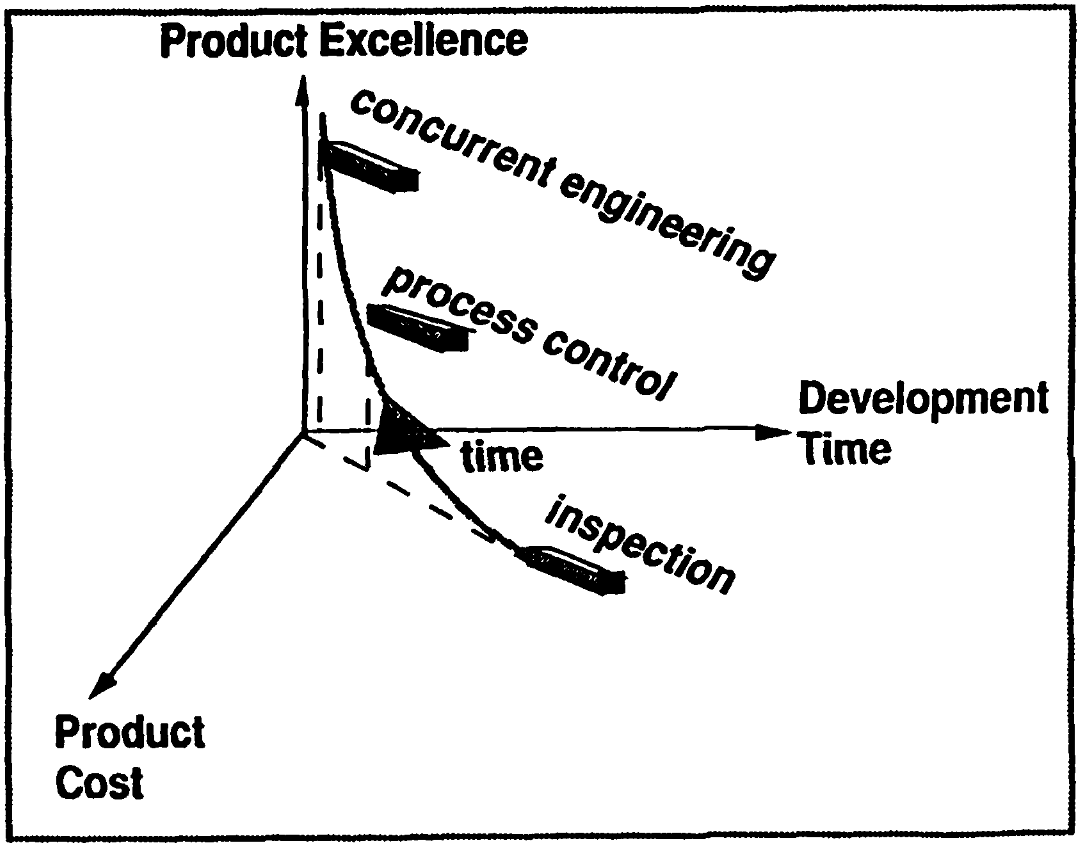
Technology for Product Excellence

- 2-1 development time reduction
- Increased quality
- Reduced life-cycle cost



Technical Underpinnings for Continuous Improvement

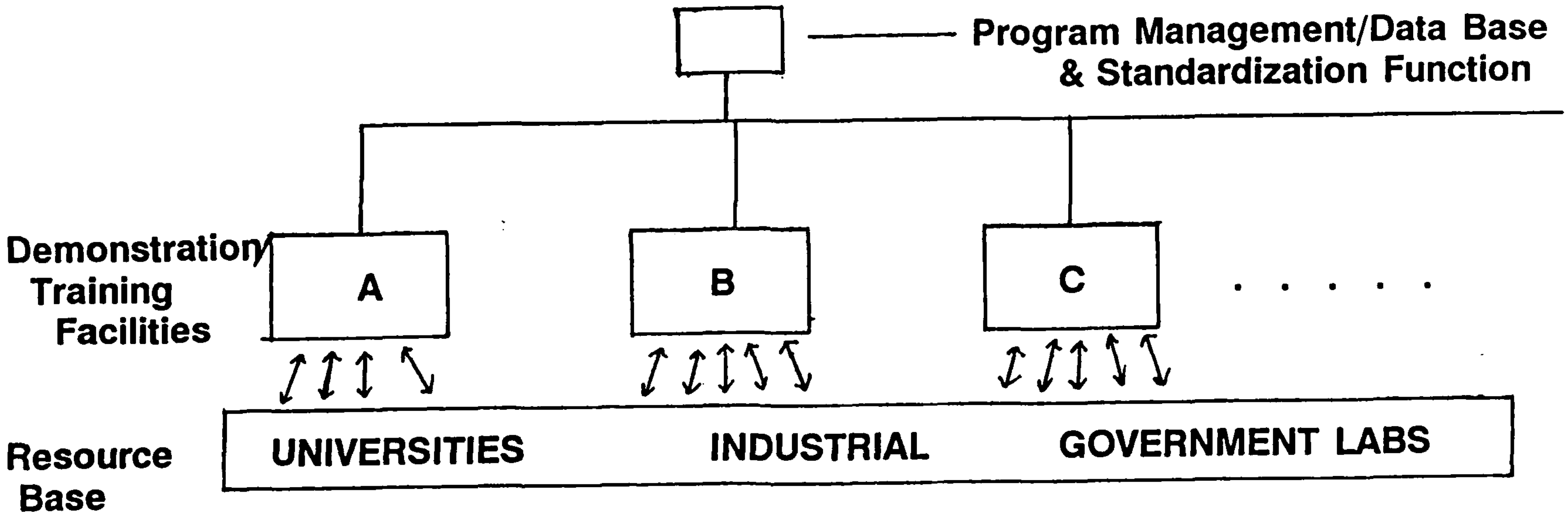
MICROFACTORY CONCEPT

Structural & Management Recommendations

- Centralized management location with very small, efficient staff
- Core technology demonstration/training facility
- Centralized facility needs to be a "neutral site" or key Army location, preferably close to customer base
- Distributed project management and training approach which takes best advantage of distributed resources, equipment.
- Project teams based upon vertically–oriented structures (R&D, consumables, equipment producers, Army systems/subsystems primes)

MICROFACTORY CONCEPT

STRAWMAN STRUCTURE BASED UPON DEMONSTRATION PROJECTS WHICH "CLUSTER" DISTRIBUTED CAPABILITIES



- Takes advantage of currently existing facilities at institutes as sites for demonstration/joint interdisciplinary projects/training
- Makes efficient use of distributed resource base at universities, industrial facilities, government labs

8.2 Technology Transfer Via Microfactories: Stephen V. Balint, Deputy Chief of Staff for Concurrent Engineering, U.S. Army Materiel Command, Alexandria, Virginia

MANUFACTURING TECHNOLOGY DIRECTIVE

DODI 4200.15, May 1985:

> "Information that is, will or may be used to define, monitor or control processes and equipment used to manufacture or remanufacture DOD materiel."

ARMY MANTECH OBJECTIVE

Apply science and engineering to the problem of manufacturing to:

- Improve the quality of Army systems
- Provide a safer working environment
- Increase productivity
- Increase competitiveness of U.S. industrial base
- Decrease cost of production and government ownership of materiel

ARMY MANTECH INITIATIVES

Capitalize on change in Army policy.
Focus resources on thrust areas.
Leverage Army resources with: industry, academia, government agencies.
Evolve centers of excellence.
Support microfactories: technology demonstrations, problem solving.
Improve the U.S. industrial base.

ARMY MANTECH THRUST AREA

Definition:

> "A set of manufacturing technology projects intended to achieve some overall, unified purpose."

THRUST AREA SELECTION CRITERIA

Opportunity for significant impact.
Depth of project objectives.
Cooperation with industry/academia
Centers of excellence potential
World class technology

ARMY MANTECH THRUST AREAS

Chemical Defense
Composite/Adhesive Bonding
Energetic Materials
Environmentally Acceptable Processes
Microelectronics Manufacturing Process Control
Missile Seekers
Night Vision/Electro Optics
Non-Destructive Evaluation
Optics Manufacturing
Soldering
Single Issues

TECHNOLOGY TRANSFER

Problem: Technical reports alone do not stimulate transfer and diffusion of technology, nor do they support that transfer.

Solution: Educate and train the industrial base by using microfactories.

MICROFACTORY FOCUS

To pilot and demonstrate new technology and export scientifically sound and proven processes.

MICROFACTORY CHARACTERIZATION

Physical focal point for specific technology.
Cooperative effort: industry, academia, government.
Equipment at a government controlled site.
Solve production problems/experimentation.
Benefit from feedback and technical reports.
Serve as the center for excellence.
Mantech dollars limited to engineering support.
No dollars for major capital investment.
Potential for "world class" capability.
Enhance Army production and U.S. industrial base.

MICROFACTORY - EDUCATION, TRAINING, SUPPORT

Education: Demonstrations, information distribution.

Training: Teaching factory.

Support: Problem solving, experimentation, data base.

ARMY MANTECH MICROFACTORIES THRUST AREA AND COMMAND

Adhesive Bonding - LABCOM MTL
Chemical Defense - AMCCOM CRDEC
Composites - LABCOM MTL
Electronics Manufacturing - CECOM
Energetic Materials - AMCCOM ARDEC
Environmentally Acceptable Processes - AMC IEA
Missile Seekers - MICOM
Night Vision/Electro Optics - CECOM CNVEO
Non-Destructive Evaluation - LABCOM MTL
Optics - AMCCOM ARDEC
Production Engineering Tooling - MICOM
Soldering - LABCOM HDL
Welding - TACOM

MICROFACTORY LESSONS LEARNED

Sole Source or "Directed"
Evolutionary, Not in Place from Start
Having "Godfather" For: Initiation, Yearly Funding, Outside Interest/Funding
Do Not Manufacture Items in Large Quantity (if at all)

8.3 A Proposed Concept of a Microfactory: David L. Olson, Colorado School of Mines, Golden, Colorado 80401

1. The microfactory is an approach to expeditiously transfer concepts, new materials and processes, and equipment from the laboratory and equipment suppliers to the manufacturing floor.

2. The microfactory will be more versatile if not a specific facility.

3. The transferable R&D results and new equipment and systems are to be identified by an Army Materiel Command sponsored microfactory coordinating group made up of representatives from Army R&D, Army manufacturers, other DOD facilities, national laboratories, universities, and welding industry.

4. The microfactory coordinating group will:
   - 4.1 Identify transferable concept or system
   - 4.2 Identify a user champion
   - 4.3 Identify the best team of expertise to achieve successful transfer into manufacturing
   - 4.4 Identify the best location or locations where a specific project should be developed, demonstrated, transferred to prototype

5. The microfactory coordinating group will meet three times a year to consider needs and opportunities and select the specific projects.
   - 5.1 Meeting (1)-Determine needs from Army manufacturers
   - 5.2 Meeting (2)-Evaluate opportunities from R and D
   - 5.3 Meeting (3)-Select most beneficial project or projects

6. Each project will have:
   - 6.1 User champion
   - 6.2 Selected project monitor
   - 6.3 Selected project manager (may be inside Army or contractor, depending on type of project and the most effective method to achieve technological transfer)
   - 6.4 Selected group of contractors which offer the best in interdisciplinary expertise.

7. A project will usually take 24 months to complete, but no longer than 36 months.

8.4 Panel for Microfactory

Dr. Andrew Crowson, (Panel Leader (ARO)
Mr. Steve Balint (AMC)
Dr. Jim Kelly (DARPA)
Mr. Donald W. Cargo (TACOM)

This four member panel promoted discussion on issues of the scope, mission, structures, selection of work, and operations of a defense welding microfactory. The following were presented as pivotal questions:

1. How do we build an organizational approach to bring the best expertise from government laboratories, university, equipment manufacturers, and users to expeditiously take an opportunity from the laboratory through scale up demonstrations, training and final utilization on the manufacturing floor?

2. Who is the best person to champion an opportunity through this microfactory and rapidly implement the opportunity in manufacturing? Is it a selected individual from the user group which would use a specific opportunity?

3. Should the microfactory be in a specific laboratory or should it be a coordinating office which draws on and promotes cooperation between numerous industrial, government and university groups and facilities?

4. How do the opportunities and needs get selected for work by the microfactory? What is the scope of the problems to be investigated? Are there short-term projects, long-term projects (~three years), or both?

5. How is a microfactory to be managed?

6. What hindrances need to be overcome in the establishment and functioning of the welding microfactory? What are the issues of intellectual property rights, consistent and dependable funding, procurement procedures and practices, security issues, selection of expertise for specific opportunities and needs, etc.?

7. How are the successes of a microfactory to be evaulated? What are its milestones?

8.5 Submitted Responses

RESEARCH PLANNING (14)

The planning of welding science research to support the microfractory concept should be based on identification of the requirements to provide welding engineers with design and control tools. Following this approach, the definition and requirements of design and control tools would be developed. Second, the missing knowledge and capabilities required to develop the tools would be identified. Third, research and development activities would be funded specifically to meet the above needs (1991).

COMBINED FUNDING (14)

Welding science and engineering should be funded in a manner to promote transfer of technology to the end user. Combined funding (i.e. 6.1, 6.2, 6.3, etc.) will be required to support the multidisciplinary, engineering and science required to provide welding engineers with appropriate design and control tools. This approach will require either aggressive marketing by program managers, or coordination by funding sources (1991).

MULTIDISCIPLINARY RESEARCH TEAMS (14)

Welding science research should be conducted by multidisciplinary research teams. Providing welding engineers with design and control tools will require computer/software expertise, human factors expertise, as well as welding science knowledge. The extension of welding science knowledge significantly beyond the present level will require multidisciplinary expertise to address the physical coupling and dynamics problems which are yet to be solved (1991).

A MARKET REPRESENTATIVE (23)

The centers are required to supply the user product which meets their needs and requirements. The function of transferring the technology falls to the project engineers as an additional burden. Everything the engineer does suffers because he is spread too thin. As has been discussed our center is an intermediary such as a "market representative" to sell our developments and transfer the technology to the world.

In any kind of research direction we must keep in mind how the research results are to be transferred not just to the shop floor but to the field. Equipment must be repairable and maintainable in the field. The Army has welders and standard weld equipment which is very limited and not high tech. The "microfactory" must provide an independent link which, much like "market reps", can transfer the knowledge to the world. There are some fundamental obstacles to overcome such as the competitive world of contractors. A quick response is needed as well as long term support. It is difficult to convince the user community to accept new materials and processes.

The microfactory should be built on existing programs that already have personnel and equipment. The organization will need to build users and sponsors into the team. The leader of the microfactory should either be an aggressive program manager from a user or provider of research and development. The leader must also be technically most competent in the relevant existing technology. The

microfactory needs to use integrated programs and personel management to achieve effective contribution from the multidisciplinary engineer scientists and technicans required to produce high quality assemblies at economical rates. The success of the microfactory can only be evaluated by the user. The microfactory should be a special laboratory since it is important to have a core group of expertise under one roof.

It was suggested that an Army program manager serve the important role of organizing information on needed work and opportunities for the funding agency to select from.

SUGGESTED METHODOLOGY TO IMPROVE PRODUCTIVITY (28)

The methodology is the following: at several facilities determine a dozen production problems involving welding that result in considerable rework. Carefully analyze the problems to determine the best corrective action starting with a statistical process control examination. Set up a parallel production effort for several problem cases based on the corrective solution. Then transfer this technology to other facilities. Competition between the various facilities for new equipment could be used as a means of increasing their support and effort.

MICROFACTORY - UNIVERSITY PERSPECTIVE (20)

1. Many different organizational concepts can work with the right leadership.

2. The organization and implementation should reflect the <u>clear</u> goals of the ARO.

3. Concepts of some worthy goals, from the university perspective are:

    Education of American students in welding science and technology to support quality implementation of technology in industry.

    Concurrent integration of welding science and research with shop floor "microfactory" development.

    The development of welding faculty in new technology areas so that they can educate with new concepts, change or update their own research directions.

    Careful evaluation of "distributive research center" concept used successfully by Paul Holloway, U. Florida, and described in tough terms by Dr. Olson (Section 8.3).

MICROFACTORY - OTHER COMMENTS (23)

Define microfactory in terms of functions and structure. Identify those functions to industry and encourage industry to "sponsor" and "advocate" who may or may not be the same person as the "champion" of that industry on microfactory efforts.

Identify microfactory teams - provide royalty payments to teams which are successful in developing and transferring technology which is commercially profitable.

Virtual factor machines and processes require object-oriented software methodologies - assists in dealing with unstructural nature of manufacturing and repair situations.

Need to address human factors which inhibit introduction of new technology. Need to identify and deal with disincentives of union labor to participate in and actively support introduction of new technology. The need and validity of the microfactory concept is demonstrated by successful use of the concept in organizations of entirely different functions and technologies.

8.6 VIABILITY OF THE MICROFACTORY CONCEPT: A SUMMARY

The consensus of the workshop participants was that a need for a central organization of welding research, development, and technological transfer was eminent. Current research activities are too remote relative to actual manufacturing practice, and an integrated approach to provide technological transfer down to the manufacturing product line is urgently needed. Even though the group felt that establishment of an integrating infrastructure would insure that the Army would receive better return on their research and systems development, there was no clear consensus on how to organize and structure such a program. There was apparent agreement that better communications across the disciplines involved in welding would result in an increase in productivity, but the fundamental interpretation of the microfactory concept for welding and assembly was determined by the frame of reference of each participant. Some participants felt the need for a central facility where interdisciplinary talents could work closely on specific problems. Other participants promoted an Army welding research and development management team that would select topical Army needs, both present and future, and coordinate the activities from the research laboratories, through the development facilities, and finally, onto the manufacturing floor. This second concept recommends that the Army establish a well balanced management team to select the project topics and to coordinate the welding activities of the best talent available throughout our nations government laboratories. This approach may be more effective in addressing the broad joining requirements of the U.S. Army, because it provides for the involvement of all the nation's welding talent to be utilized in an efficient discipline-specific way.

9.0 RECOMMENDATIONS

The following considered recommendations resulted from analysis of the workshop results:

1. The welding research and development needs identified by the workshop should be prioritized by the U.S. Army. Prioritization should be based on present and future requirements of the Army to make technical and structural assemblies.

2. Every attempt should be made to correlate the prioritized welding and joining research needs with the apparent process and material capabilities (opportunities) identified by the workshop. This practice will produce the greatest technological advancement in manufacturing of technical and structural assemblies (the greatest return for the investment).

3. Because welding or joining is a major factor in fabrication of economical military structures of high integrity, an organization (a microfactory) should be established to coordinate the welding activities relating to specific Army structures.

4. The recommended organization (microfactory) must possess a broad technical base, and should include expertise in materials, processes, and design. The organization needs disciplinary depth of welding sciences, as well as the technological breadth needed for manufacturing. This broad technical base is necessary for either a management group of a fully equipped facility.

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3. R.A. Kelsey, G.W. Oyler, and C.R. Felmley, Jr., Welding Research Council, Bulletin 293, N.Y., N.Y., April (1984).

4. D.L. Olson, "United States Army Welding Research and Development Topical and Coordination Meeting", CSM Report MT-CWR-085-001, Colorado School of Mines, Golden, Colorado (1985).

5. J.G. Bollinger, et al., "Control of Welding Processes", National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, Publication NMAB-421, National Academy Press (1987).

6. Harvey R. Castner, Edison Welding Institute, Columbus, Ohio.

7. Herschel B. Smartt, Idaho National Engineering Laboratories, Idaho Falls, Idaho.

8. Carl E. Cross, Martin Marietta Astronautics, Denver, Colorado.

9. Michael Wells, David Taylor Research Center, Annapolis, Maryland.

10. Gerald DePoorter, Colorado School of Mines, Golden, Colorado.

11. Tom W. Eagar, Massachusetts Institute of Technology, Cambridge, Massachusetts.

12. W.A. Bud Baeslack III, Ohio State University, Columbus, Ohio.

13. Bob Rivett, Edison Welding Institute, Columbus, Ohio.

14. Jim Key, Idaho National Engineering Laboratory, Idaho Falls, Idaho.

15. John D. Landes, University of Tennessee, Knoxville, Tennessee.

16. Paul W. Holsberg, David Taylor Research Center, Annapolis, Maryland.

17. John Lippold, Edison Welding Institute, Columbus, Ohio.

18. David L. Olson, Colorado School of Mines, Golden, Colorado.

19. Kim W. Mahin, Sandia National Laboratory, Livermore, California.

20. Raymond G. Thompson, University of Alabama at Birmingham, Birmingham, Alabama.

21. Michael J. Cieslak, Sandia National Laboratories, Albuquerque, New Mexico.

22. Stan Waxman, Army Research and Development Engineering Center, Picatinny Arsenal, New Jersey.

23. Unidentified Workshop Participant, March (1991).

24. Bob Kratzenberg, General Dynamics, Land Systems Division, Limo, Ohio.

25. Ted Anderson, Texas A and M University, College Station, Texas.

26. Chris M. Fortunko, Materials Reliability Division, NIST, Boulder, Colorado.

27. Thomas A. Siewert, NIST, Boulder, Colorado.

28. Edward A. Metzbower, U.S. Naval Research Lab., Wash., DC.

29. Paul Burgardt, EG&G Rocky Flats, Golden, Colorado.

30. Dawn White, MTS Systems Corporation, Minneapolis, Minnessota.

31. Martin Kline, Babcock and Wilcox, Lynchburgh, Virginia.

32. Jerry E. Jones, American Welding Institute, Knoxville, Tennessee.

33. Eric K. Johnson, EG&G Mound Applied Technology, Miamisburg, Ohio.

34. Phillip A. Parrish, DBM International Inc., Arlington, Virginia.

35. O.J. Davis, Ingalls Shipbuilding, Litton, Pascagoula, Mississippi.

36. Glen R. Edwards, Colorado School of Mines, Golden, Colorado.

37. Jim Geis, ERC/Ogden, Inc., (for U.S. Army Harry Diamond Labs., Adelpi, Maryland.

11.0 LIST OF PARTICIPANTS

ATTENDANCE

ADVANCED WELDING SCIENCE FOR DOD APPLICATION WORKSHOP

"The Genesis of the Army Welding Microfactory"

March 20-22, 1991

Name	Company
Ted Anderson	Texas A & M
Bud Baeslack	Ohio State University
Steve Balint	U.S. Army Materiel Command
Clifton Boyd	USA TACOM
Paul Burgardt	DOE/Rocky Flats Plant
Don Cargo	USA TACOM
Harvey Castner	Edison Welding Institute
Edward Chen	Army Research Office
Mike Cieslak	Sandia National Lab
Darryl Colvin	USA Benet Laboratories
Charles Connely	FUTEC
Carl Cross	Martin Marietta
Andrew Crowson	Army Research Office
Stan David	Oak Ridge National Lab.
O.J. Davis	Ingalls Shipbuilding
Gerald DePoorter	Colorado School of Mines
Thomas Eagar	MIT
Glen Edwards	Colorado School of Mines
Jamie Florence	USA TACOM
Chris Fortunko	NIST
Robert Frost	Colorado School of Mines
Steve Gedeon	Welding Inst. of Canada
Jim Geis	ERC/Ogden Inc.
Paul Holsberg	USN DTRC
Brian Hornbeck	USA Ft. Belvoir RD Ctr.
Eric Johnson	EG&G Mound
Jerry Jones	American Welding Institute
Jim Kelly	DARPA
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Martin Kline	Babcock & Wilcox
Bob Kratzenberg	General Dynamics
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Phillip Parrish	BDM Int. Inc.

Name	Company
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Tom Siewert	NIST
Herschel Smartt	INEL
Ray Thompson	Univ. of Alabama-Birmingham
Hans Vanderveldt	American Welding Institute
Stan Waxman	DOD/Dept. of Army
Robert Weber	USA CERL
Michael Wells	USN DTRC
Dave Westphal	EG&G Rocky Flats Plant
Dawn White	MTS Systems Corp.
Sara Yob	USA TACOM
Glenn Ziegenfuss	American Welding Society

APPENDIX

Examples of Workshop Materials

ARO WORKSHOP

SAMPLE

Bullet Slide Format for Need or Opportunity

Name ______________________________

Affiliation______________________________

Address______________________________

____

TITLE (please keep less than ten word title)

Scope ~50 to 80 word paragraph

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